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THE EFFECT OF CONFIGURATION ON STRENGTH, DURABILITY, AND HANDLE OF KEVLAR FABRIC-BASED MATERIALS

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for Langley Research Center

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16. Abstract

Five Kevlar based laminates and three Kevlar based coated materials were designed, hand made, and tested against comparative conventional Dacron based materials for strength, peel, tear, puncture, creases, and handle. Emphasis was placed on evaluating geometric orientation of constituents, use of elastomeric film in place of high modulus films, and the use of Flying Thread Loom bias reinforcement of Kevlar yarns. Whereas, the performance of the Kevlar laminates was severely degraded by crease effects, significant gains in overall performance factors were shown for the coated Kevlar materials.

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Certain commercial equipment, special equipment and materials are identified in this report in order to adequately specify the experimental procedures. In no case does such identification imply recommendation or endorsement of the product by NASA, nor does it imply that the equipment or materials are necessarily the best or the only materials available for the purpose.

THE EFFECT OF CONFIGURATION ON STRENGTH, DURABILITY, AND HANDLE OF KEVLAR® FABRIC-BASED MATERIALS

By L. L. Rueter and J. B. Munson
Sheldahl, Inc.

SUMMARY

The purpose of this investigation was to develop prototype high strength composite materials, incorporating Kevlar-49® fabric as the structural element, for use in the fabrication of flexible inflatable structures. Other objectives were to determine the effect on flexibility of locating the fabric near the neutral plane, to evaluate an open scrim bias ply, and to obtain a more flexible laminate by including an elastomeric film.

Various handmade laminate and coated material configurations were evaluated for tensile strength, peel strength, crease effects, tear resistance, flexibility, "handle" and puncture resistance. One laminated and one coated material with Dacron® fabric were used as controls. Adequate peel strength, tear resistance and puncture resistance were demonstrated. The geometric and mechanical factors influencing tear resistance were found to be the same for Kevlar and Dacron materials. Puncture resistance was found to be inversely related to fabric stiffness for the laminated materials and to be inversely related to coat thickness for coated materials. Creasing of Kevlar-based laminates was found to severely degrade the strength. However, only small to moderate degradation was found for the coated Kevlar-based materials. After crease degradation, coated Kevlar-49 materials still exhibited about twice the strength-to-weight ratio of the coated Dacron control material. The strength-to-weight advantages of the uncreased Kevlar laminates were largely nullified by creasing. Creased, Kevlar laminate strength-to-weight ratios became comparable to the creased Dacron-control laminate.

The coated materials showed significant improvement over the laminates in fabric handle. By repositioning the Kevlar fabric from an outer-plane to the mid-plane of the coated materials the quantitative handle measure (handle modulus) was reduced about 39 percent and the strength loss caused by creasing was reduced from 9 percent to 2 percent. This demonstrates the importance of constituent laminar arrangement.

Uniaxial coupon tests of materials with diagonal fabric elements were found to degrade tensile strength and to show unrealistically high variability of strength and elongation with temperature. The high variability was found to be a result of thermomechanical phase transitions in the adhesive in conjunction with the unstrained edges which influenced the structural contribution of the diagonal fiber elements of the coupon specimens. For applications to be packed and folded, Kevlar is not particularly advantageous unless crease

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degradation can be controlled. However, the superior performance of Kevlar coated materials compared to similar Dacron coated materials was shown to be practical for applications where creasing occurs.

INTRODUCTION

Considerable interest exists in both private industry and government relating to the structural use of filamentary materials. These materials have a direct application as reinforcement of memebrane materials for inflatable structures. Such structures include tethered aerostats, airships, long duration superpressure balloons, zero-pressure balloons, inflatable helicopter floats, inflatable boats, and pressure vessels. Figure 1 shows several of these end uses.

The new organic high strength, high modulus aramid fiber, Kevlar-49* recently developed and marketed by DuPont is of special interest. This fiber, previously designated "PRD-49" (Preliminary Research and Development Number 49), offers a strength-to-weight ratio 2 to 3.5 times that of Dacron and 10 times that of steel. The strength-to-weight ratio of Kevlar exceeds that of all other materials which can be fabricated with conventional textile technology.

The general objective of this study was to promote research on applications of Kevlar fabrics for inflatable structures. In particular, coated and laminated Dacron-fabric materials successfully used in such structures were compared with coated and laminated, Kevlar-reinforced counterparts.

In Reference 1 the importance of the fiber-reinforcement pattern and geometric configuration of laminated materials were explored experimentally by bi-axial cylinder testing. It was concluded that significant improvement in shear strength could be made by varying the pattern of reinforcement.

Reference 2 presents an analytical approach for optimization of the planar geometry of the materials and reinforcements studied in Reference 1. Good agreement was obtained between the experimental and analytical efforts.

Reference 3 documents a thorough research of Kevlar-reinforced coated and laminate materials compared with conventional Dacron materials. These materials were tested for tensile and shear strengths, crease degradation, tear strength, abrasion resistance, flex life, blocking, and permeability. The Kevlar materials were found to be equal or superior to the Dacron materials in all tests except crease and tear. This research indicated that Kevlar fabrics are degraded by creasing when bonded in laminates or

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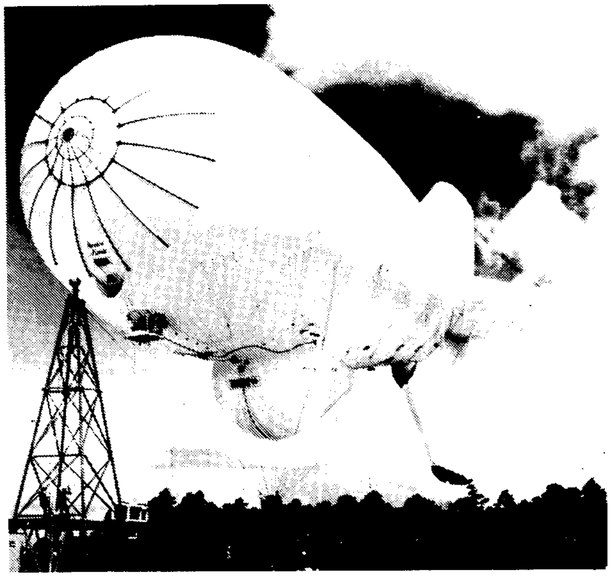
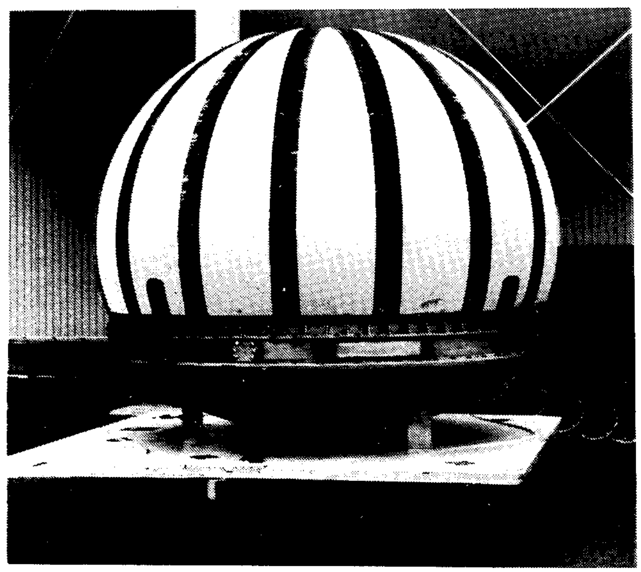
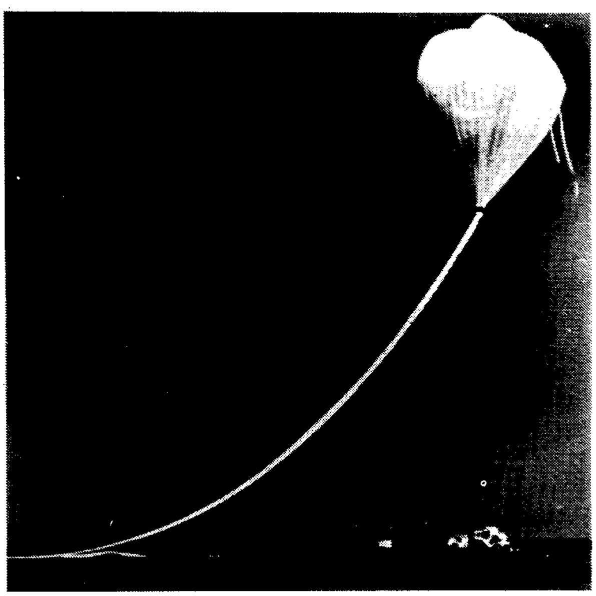
*DuPont markets two forms of Kevlar: "Kevlar 49" and "Kevlar 29" (previously designated as fiber B). Kevlar 29 has the same breaking strength as Kevlar 49, but its modulus is about 50 percent that of Kevlar 49. Only Kevlar 49 was investigated in this study.



(a) 7000 m^3 Tethered Balloon



(b) 2-Meter Diameter, 1 Atmosphere Pressure vessel



(c) 1,000,000 m^3, Free-Flight Balloon

Figure 1. Structures Using Yarn-Reinforced Membrane Materials

encapsulated by conventional fabric coatings. A qualitative fault in the Kevlar materials was the undesirable stiffness, or poor "handle".

An additional objective of this study was to improve the handle properties of materials described in Reference 3. The selection of flexible materials for inflatable structures to be packaged and deployed is strongly influenced by the subjective quality, handle. Soft, pliable, easily folded materials are said to have good "handle." The Kevlar-based materials discussed above are characteristically stiff and resistant to hard creasing. The materials in Reference 3 had the fabric located near the exterior surface of the laminated or coated composites. This aids in obtaining high strength lap seams and splices, but the external location of high modulus fibers contributes to a poor handle characteristic.

Laminated and coated material samples, about one square meter in area, were handmade to evaluate the effect of locating the high modulus fabric near the center plane of the materials. The scope of the research did not permit sample manufacture on full-scale production machinery.

Strength testing was limited to coupon tensile specimens. The strength characteristics reported are, therefore, primarily comparative and qualitative in value. Other material comparisons were based on folding, tear, peel and puncture tests, and special handle tests provided by NASA. In the following sections, design and construction details, test methods, results, and conclusions are discussed in detail.

DEFINITION OF TEST MATERIALS

The test materials investigated are shown in Figure 2. Throughout this report individual test materials are identified by row number and column letter (1a, 1b, etc.) Variations in material constituents occur from left to right (column variable), while variations in material construction occur from top to bottom (row variable). Materials 1 through 4 are laminates, and 5 and 6 are coated fabrics. Materials in column (a) are baseline materials using Dacron fabric. Materials in columns (b) and (c) have Kevlar fabric substituted in place of the Dacron. Materials in column (c) have an additional layer of Kevlar-49 bias yarns, as shown in Figure 5a. Variations in material construction (3b and 6b) were made to relocate the fabric nearer to the neutral plane. Material 4c was configured to evaluate a Hytrel® coating and is an exception to the conventions above. This material is closely related to material 2c. Hytrel coating could not be directly substituted for the Mylar® film since Hytrel has poor permeability in the thickness considered. A layer of Saran (commercial Saran Wrap film by Dow Chemical) was included in 4c to obtain a laminate with permeability equivalent to 2c.

The basic mechanical properties of the Dacron and Kevlar fabrics used are given in TABLES 1 and 2, respectively. Properties of the membranes and coatings are provided in TABLE 3. Except for variations from the assembly process, total thickness was held constant for all variants in Figure 2.

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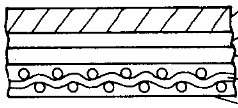
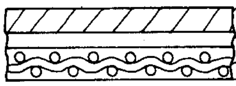
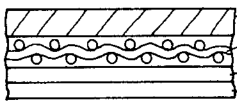
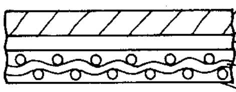
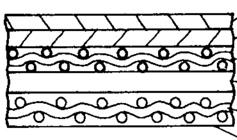
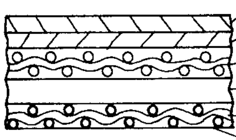
	a	b	c
	Laminate Materials		
1 	Tedlar ▶ Mylar ▶ Mylar ▶ Dacron,1000 d, 13 x 13 Adhesive (coat)	Tedlar Mylar Mylar ▷ Kevlar-49* Adhesive (coat)	
2 		Tedlar ▶ Mylar ▶ Kevlar-49* Adhesive (coat)	Tedlar ▶ Mylar ▶ ●FTL Bias ▷ Kevlar-49* Adhesive (coat)
3 		Tedlar ▶ Kevlar-49* ▶ Mylar ▶ Mylar	
4 			Tedlar ▶ Saran ▶ Hytrel ▶ ●FTL Bias Kevlar-49* Adhesive (coat)
	Coated Materials		
5 	Hypalon ▷ Polyurethane ▷ Dacron, Bias Ply** ▷ Neoprene ▶ Dacron† Adhesive (coat)	Hypalon Polyurethane Dacron, Bias** Neoprene Kevlar-49†† Adhesive (coat)	
6 		Hypalon ▷ Polyurethane ▷ Kevlar-49†† ▷ Neoprene ▶ Dacron Bias** Adhesive (coat)	Hypalon Polyurethane ▷ ●FTL Bias ▶ Kevlar-49†† ▶ Polyurethane

*61 g/sq m (1.8 oz/sq yd) plain weave fabric.
**48 g/sq m (1.4 oz/sq yd) plain weave fabric.
†110 g/sq m (3.25 oz/sq yd) plain weave fabric.
††95 g/sq m (2.8 oz/sq yd) plain weave fabric.
▷Peel test interface (attempted).
▶Peel test interface (successful).
● 380 denier, Kevlar yarn 60° FTL, equally spaced 1.1 cm (0.43 in.) apart.

Figure 2. Matrix of Test Materials. Upper layer shown would be the exterior of an inflatable structure

TABLE 1. - Properties of Dacron-Fabric Components, Metric Units
(English units in parentheses)

Characteristic \ Application	5a, 5b, 6b	5a	1a
Weight	0.047 N/m^2 (1.4 oz/yd^2)	0.108 N/m^2 (3.25 oz/yd^2)	0.126 N/m^2 (3.8 oz/yd^2)
Strength: Warp	6100 N/m (35 lb/in.)	27,000 N/m (155 lb/in.)	39,400 N/m (225 lb/in.)
Fill	6100 N/m (35 lb/in.)	27,000 N/m (155 lb/in.)	39,400 N/m (225 lb/in.)
Weave Type	Plain	Plain	Plain
Fabric Finish	Scoured and heat set	Scoured and heat set	Scoured and heat set with 5 to 10% by weight of polyvinyl acetate
Yarn Count	39/cm x 39/cm (18/in. x 98/in.)	20/cm x 20/cm (50/in. x 50/in.)	5/cm x 5/cm (13/in. x 13/in.)
Yarn Size	40 denier	220 denier	1000 denier
Yarn Twist	9 turns/cm (23 turns/in.)	1 turn/cm (3 turns/in.)	4 turn/m (0.1 turns/in.)
Filament Count	27/yarn	50/yarn	192/yarn
Filament Strength	570 NM/m^2 (0.83×10^5 lb/in.^{2})	1030 MN/m^2 (1.5×10^5 lb/in.^{2})	1030 MN/m^2 (1.5×10^5 lb/in.^{2})
Filament Modulus	13.8 GN/m^2 (2×10^6 lb/in.^{2})	13.8 GN/m^2 (2×10^6 lb/in.^{2})	13.8 GN/m^2 2×10^6 lb/in.^{2})
Density	1380 kg/m^3 (0.05 lb/in.^{3})	1380 kb/m^3 (0.05 lb/in.^{3})	1380 kg/m^3 (0.05 lb/in.^{3})

TABLE 2. - Properties of Kevlar-49 Fabric Components, Metric Units
(English units in parentheses)

Characteristic \ Application	1b, 2b, ac, 3b, 4c	5b, 6b, 6c
Weight	0.60 kg/m^2 (1.8 oz/yd^2)	0.090 kg/m^2 (2.7 oz/yd^2)
Strength: Warp	39,400 N/m (225 lb/in.)	74,400 N/m (425 lb/in.)
Fill	39,400 N/m (225 lb/in.)	74,400 N/m (425 lb/in.)
Weave Type	Plain	Plain
Fabric Finish	Scoured	Scoured
Yarn Count	13/cm x 13/cm (34/in. x 34/in.)	20/cm x 20/cm (50/in. x 50/in.)
Yarn Size	195 denier	195 denier
Yarn Twist	4 turns/m (0.1 turn/in.)	4 turns/m (0.1 turn/in.)
Filament Count	134/yarn	134/yarn
Filament Strength	3620 MN/m^2 (5.25×10^5 $lb/in.^2$)	3620 MN/m^2 (5.25×10^5 $lb/in.^2$)
Filament Modulus	131 GN/m^2 (1.9×10^7 $lb/in.^2$)	131 GN/m^2 (1.9×10^7 $lb/in.^2$)
Density	1450 kb/m^3 (0.052 $lb/in.^3$)	1450 kg/m^3 (0.052 $lb/in.^3$)

TABLE 3. - Properties of Film, Adhesive, and Coating Components, Metric Units (English units in parentheses)

Characteristic / Component	Application	Description	Tensile Strength at 22°C (72°F)
Tedlar	1a, 1b, 2b, 2c, 3b, 4c	38.1μm (1.5 mil) thick, DuPont polyvinyl fluoride film, type 30, adherable both sides, "L" gloss, titanium dioxide pigment	55MN/m^2 (8,000 lb/$in.^2$)
Mylar	1a, 1b, 2b, 2c, 3b, 4c	6.35μm (0.25 mil) thick, DuPont type S polyester film	138 MN/m^2 (20,000 lb/$in.^2$)
Adhesive	A - 1oz	Aromatic polyester resin cured with di-isocyanate for hydrolytic stability	10 MN/m^2 (1,500 lb/$in.^2$)
Hypalon	5a, 5b, 6b 6c	54.5μm (2.1 mil) thick, chloro-sulfonated polyethylene with titanium dioxide pigment	14 MN/m^2 (2,000 lb/$in.^2$)
Neoprene	5a, 5b, 6b	95.3μm (3.75 mil) thick, low temperature noncrystalline poly-chloroprene with lead cure system for hydrolytic stability	24 MN/m^2 (3,500 lb/$in.^2$)
Urethane	5a, 5b, 6b, 6c	71.2μm (2.8 mil) thick, B.F. Good-rich low temperature polyurethane formulated for high hydrolytic stability, ultraviolet resistance and heat stability. Carbon black pigment. Fabric surfaces to be coated are treated with isocyanate-type primer	34 MN/m^2 (5,000 lb/$in.^2$)
Saran	4c	10.0μm (0.75 mil) thick polyvinyl-idene chloride; Dow commercial grade Saran wrap	34 - 55 MN/m^2 (5000 - 8000 lb/$in.^2$)

FABRICATION OF TEST MATERIALS

All material samples were hand lay-ups. To simulate the material orientation of web-process production machinery, all components were oriented with respect to a common machine (warp) direction. Each sample was marked with the machine direction and the designated code of Figure 2 (1a, 1b, etc.)

Laminate Materials

All laminate samples (materials 1 through 4) were made at Sheldahl, Inc., Northfield, Minnesota. A polyester thermosetting adhesive, Sheldahl A-102 applied in solution with methylene chloride was used as the bonding agent. This adhesive has been extensively used for film and fabric laminates. The samples were combined with heat and pressure using a platen press, Figure 3. Maximum sample size for the press was 30.5 cm by 30.5 cm (12 in. by 12 in.) Test materials were assembled using constituent layers of larger dimensions to permit handling by the edges. Ten samples of each laminate were made.

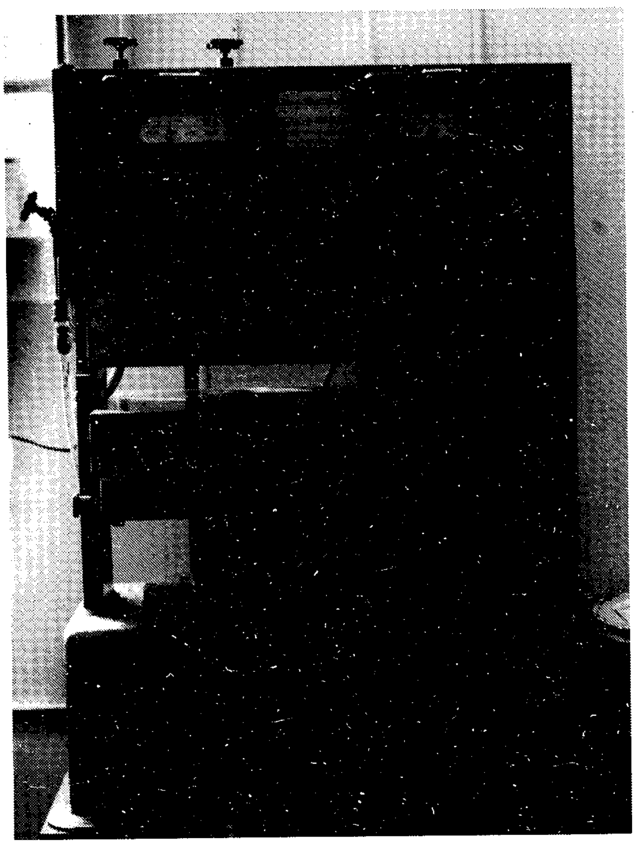


Figure 3. Platen Press

The samples were assembled on a polycarbonate surface 40.6 cm by 40.6 cm (16 in. by 16 in.) Because of lighting conditions and film reflectance, air entrapped during film lay-up was easier to locate when the surface was slightly inclined. First, Tedlar® film exterior surface down, was tensioned to remove creases, and taped to the work surface at the corners (Figure 4a). Subsequent layers of material were added after applying the required amount of adhesive. Film layers were cut slightly smaller than the lay-up surface and wound on 15-cm (6-in.) diameter cores. Air pockets were minimized by unrolling the film from the core (Figure 4b). After the lay-up was complete, the sample was trimmed to 30.5 cm (12 in.) square with a metal template. The adhesive quickly developed sufficient strength to maintain position of the layers until the sample was laminated.

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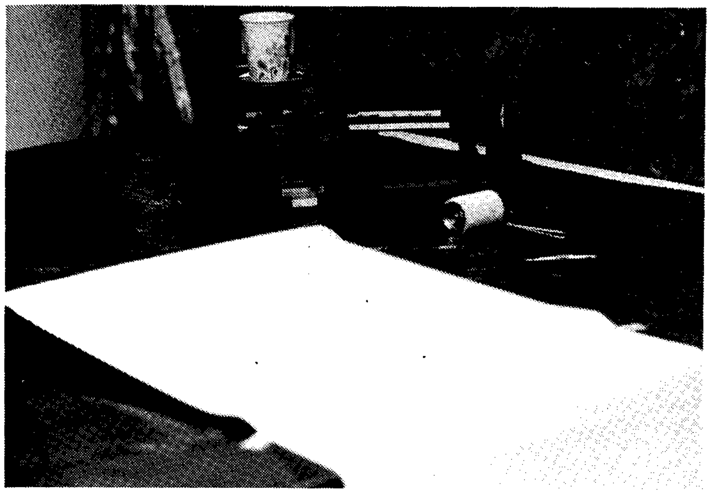
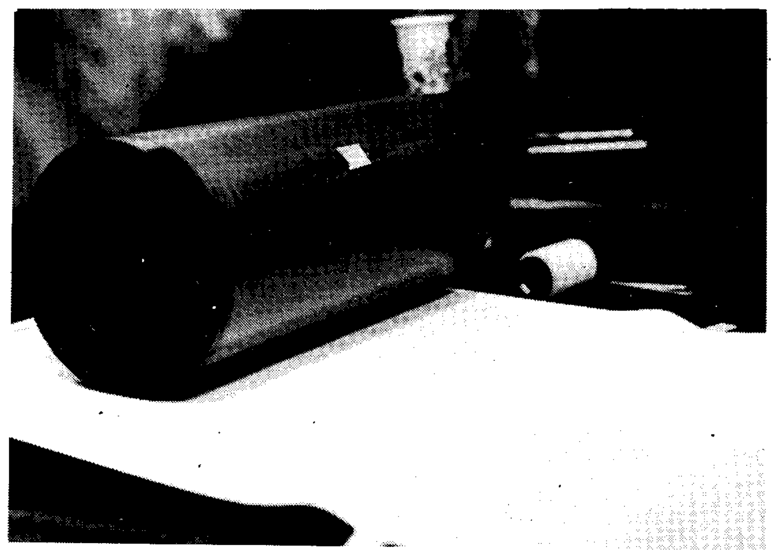
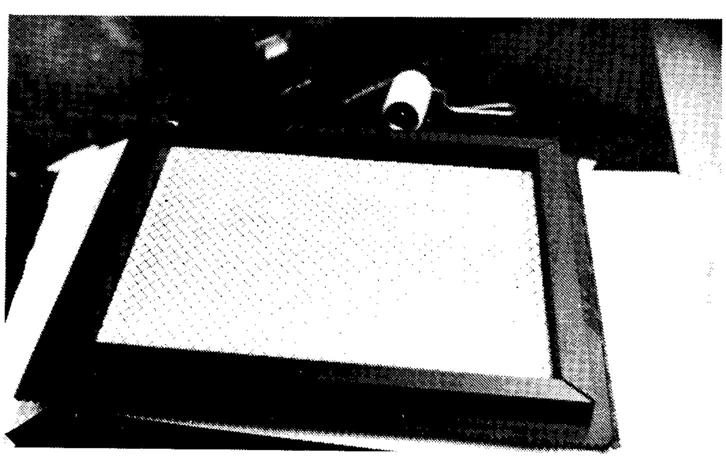


(a)

(b)





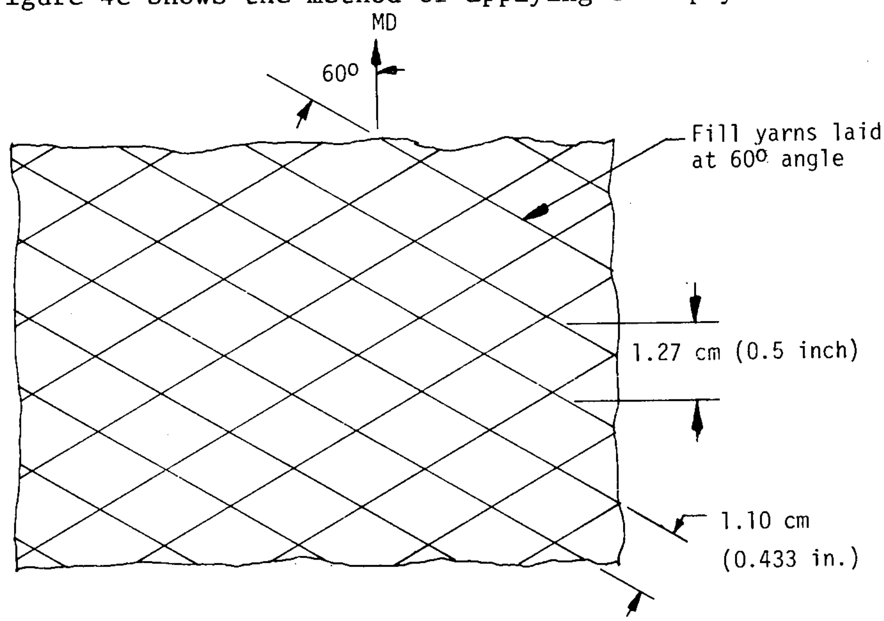
(c)

Figure 4. Hand Lay-Up of Laminate Samples

Adhesive thickness was controlled by weighing out the required amount, and spreading with a roller. Tare weight of the container was measured after filling with adhesive and emptying it, and the roller was presaturated with adhesive to compensate for the weight of material remaining on the roller and container.

Kevlar-49 yarn, 380 denier, was used for the 60° bias ply (Figure 5a). This configuration is readily produced in conjunction with a web-type lamination process and has been commonly used to increase the shear stiffness of laminates. Yarns were positioned on a rectangular frame with notched edges, Figure 5b. Figure 4c shows the method of applying this ply to the sample.

(a)



(b)

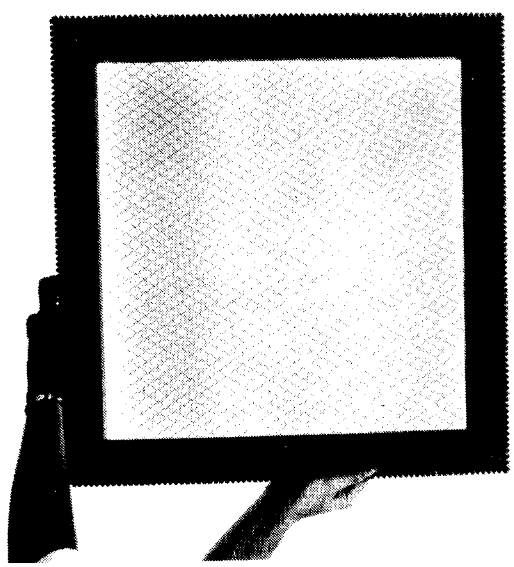


Figure 5. Kevlar Yarn Bias Ply

After lay-up, the sample was placed between layers of release paper, blotter paper, and aluminum wear plates (Figure 6) before placing it in the press. Blotter paper serves to distribute the pressure loading around thickness variations caused by wear-plate surface irregularities and bias yarns. The release paper was included to prevent bonding the blotter paper to the specimen. The wear plates protect the surface of the press platens.

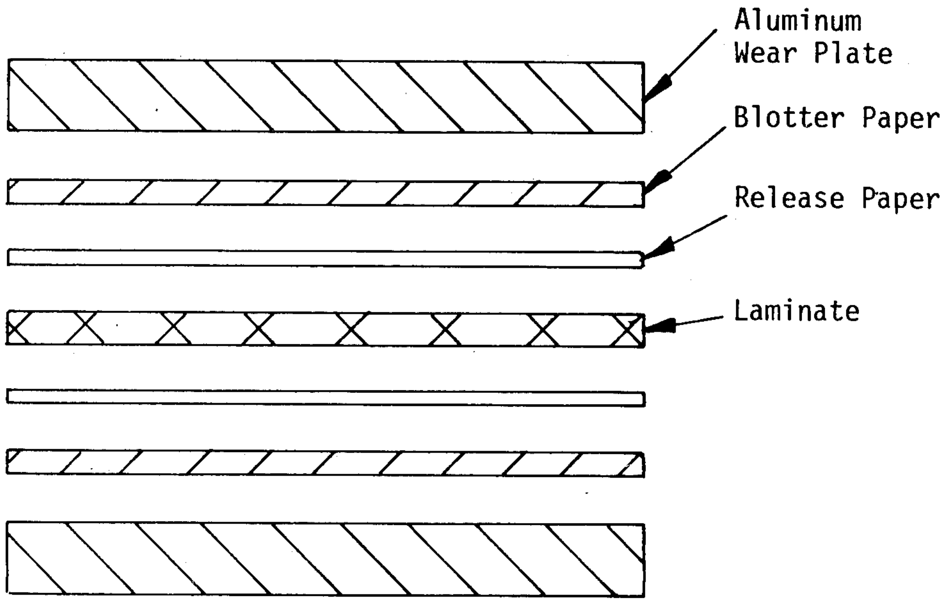


Figure 6. Laminate Sample Prepared for Pressing

Press platens are provided with temperature controlled electric heaters and a water-cooling system. Ram pressure is produced hydraulically using an air pressurized reservoir, and dwell time is controlled by the operator.

An important feature of this laminating process is that both heating and cooling occur while the sample is restrained by pressure. Cooling the sample under pressure minimizes shrinkage. Web-process laminators ordinarily do not restrain the material during cooling.

Several test samples were made to establish the following process parameters, based on peel testing and appearance.

Heat-cycle temperature:	127°C (260°F)
Dwell time:	15 seconds
Cool-down temperature:	66°C (150°F)
Ram force:	9.8×10^4 N (11 tons)
Air pressure:	1.0×10^6 N/m^2 (150 psi)

At the beginning of a sample run the press was cycled to check pressure and temperature. During heating, platen temperature was monitored with a separate pyrometer and temperature controls adjusted as required. Ram pressure was verified by monitoring air pressure in the hydraulic reservoir.

A calibration curve relating reservoir pressure to ram pressure was used to adjust the air pressure regulator as required. Unless obvious sample defects were noted during the run, no further checks were made on pressure or temperature.

The material sandwich was placed in the press and ram pressure and platen heaters were turned on. After the required heating time, the heater current was turned off and water circulated through the platens. After cooling to the specified temperature, the press was opened and the sample removed. The platen heat exchanger was purged of coolant before beginning a new heating cycle.

Coated-Fabric Materials

These were coated and combined by Chemprene, Inc., a division of the Richardson Comapny, using raw materials supplied by Sheldahl. The available laboratory-scale coating equipment limited the product to a width of 0.38 m and a length of 3 m (15 in. by 9 ft). The amount of scrap produced was about twice the original estimate of 25 percent, which limited the amount of testing that could be performed.

Bias yarns (Figure 5a) were combined with the adjoining structural fabric before coating. The metal frames could not be used because of the 3 m sample length required. A substitute was made with nails positioned on 1.27 cm (0.5 in.) centers around a plywood rectangle 0.61 m by 3.8 m (2 ft by 12.5 ft). Fabric was placed inside the rectangle and the yarn pattern of Figure 5a produced with Kevlar yarn. A dilute adhesive solution (3- to 5-percent solids) was applied to bond yarn and fabric together. After air drying, the yarns were trimmed flush with the fabric edge. During the coating process, the fabric and bias ply were treated as a single layer. No difficulties associated with the bias yarns were encountered during the coating process.

TEST PROGRAM

Tests of tensile strength, crease degradation, tear strength, interlaminar peel strength, puncture resistance, and handle were performed on the two baseline Dacron laminates and the eight Kevlar composites. The test procedures and equipment are discussed in the following paragraphs.

Strength Tests

Ultimate tensile strength and elastic properties were determined by uniaxial testing. Inter-laminar bond strength was investigated by peel tests.

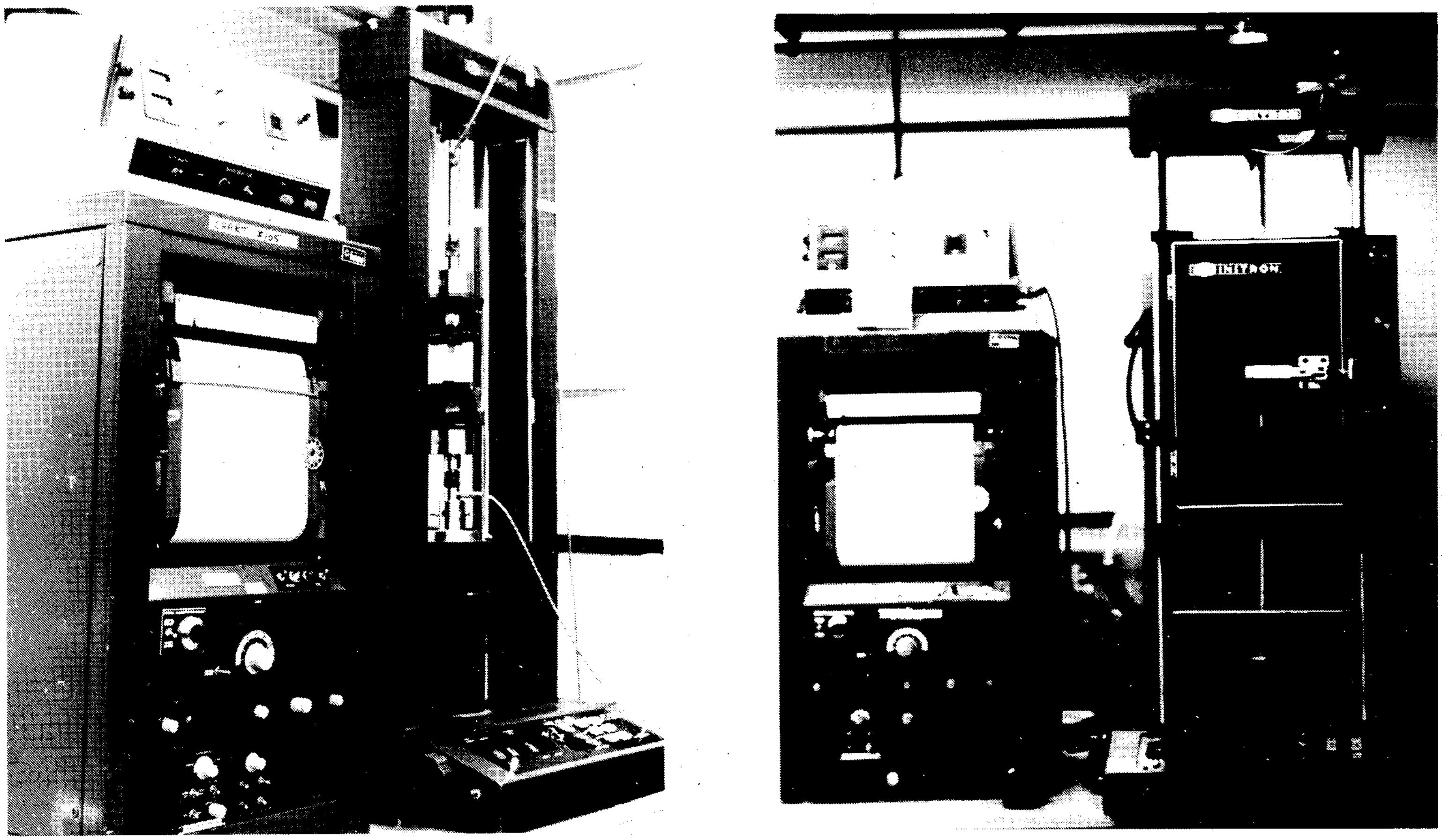
Uniaxial tensile tests. - The uniaxial tensile tests were performed using Federal Test Method 5102 which employs a sample size 2.54-cm (1-in.) wide and a 7.6-cm (3-in.) grip separation. The grip separation rate used for these tests was 5.1 cm/min (2 in./min). Five specimens of each material were tested at specimen orientations of machine direction (warp), transverse direction (fill), and 45° left and right of machine direction and at temperatures of 60°C, 22°C, and -51°C, ±1.7°C (140°F, 72°F, and -60°F, respectively, ±3°F).

All tests were conducted on a Model 114 Instron Testing Machine (Figure 7) having a capacity of 4,448 N (1000 lb) and variable strain rates up to 1.27 m/min (50 in./min) for loads up to 2224 N (500 lb). Accuracy is one percent of full-scale reading. The recorder has a variable load range and can be driven to 1.27 m/min (50 in./min) paper speed. Figure 7a shows the machine as used for 22°C tests and Figure 7b shows the machine with an environmental chamber in place for testing at elevated and sub-zero temperatures.

The Thwing-Albert sample cutter shown in Figure 8 provides a precision sample width of 2.54 cm (1 in.) Three methods were used for clamping the custom material test specimens. An ideal method would apply a uniform clamping force, independent of any specimen thickness change caused by loading. Because of the clamping force required for high strength Kevlar materials, hydraulically actuated jaws (Figure 9a) were used. Since these are limited to a temperature range of 0°C to 50°C (35°F to 120°F) it was necessary to use D-ring grips (Figure 9c) for the cold tests and screw clamp jaws (Figure 9b) at elevated temperatures.

The D-ring grips are superior for cold tests because the clamping force is not affected by frost formation on the jaw faces.

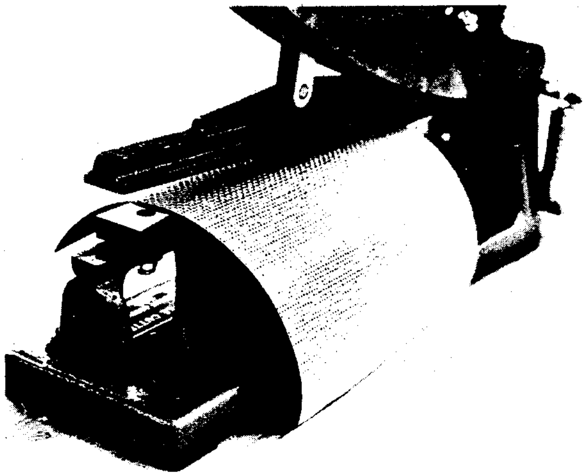
Figure 9d shows the material wrap configuration which provides efficient clamping, but complicates attainment of uniform free specimen lengths.



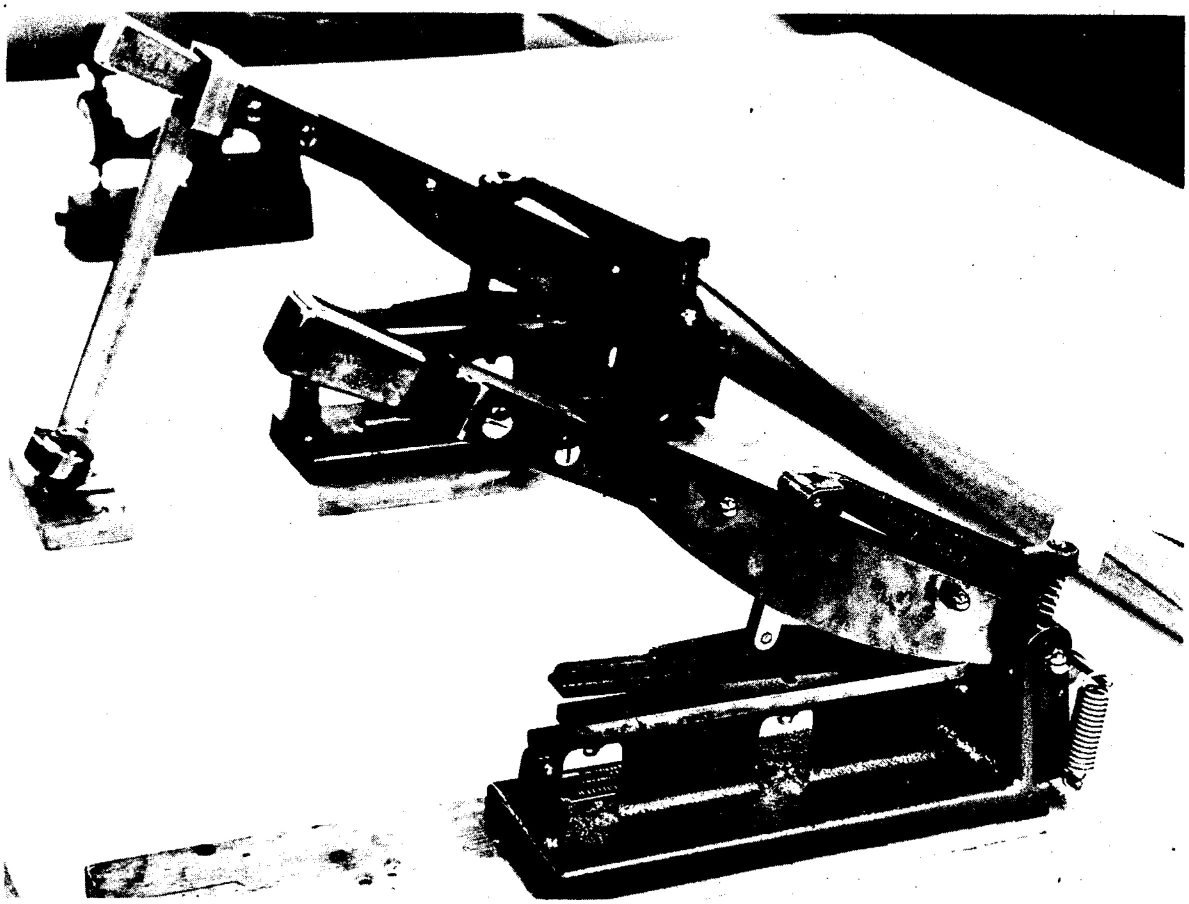
(a) Ambient Temperature Test Arrangement

(b) Variable Temperature Test Arrangement

Figure 7. Instron Testing Facility

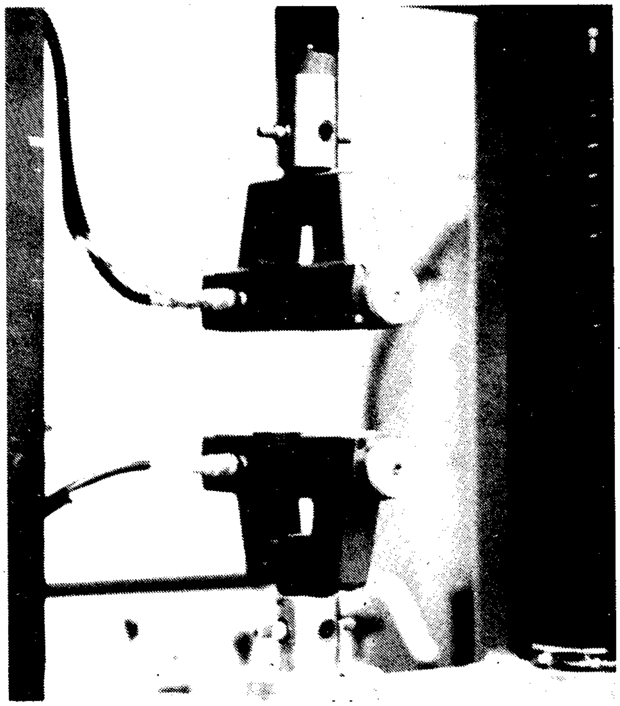


(a)

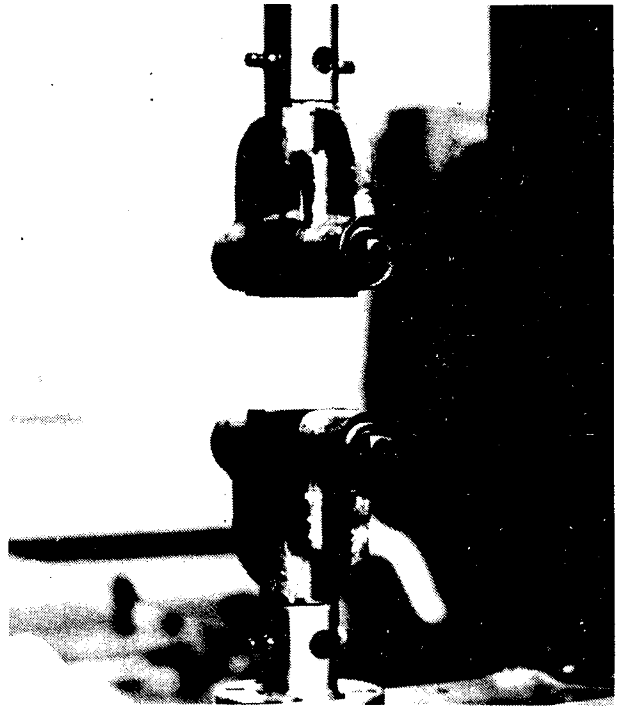


(b)

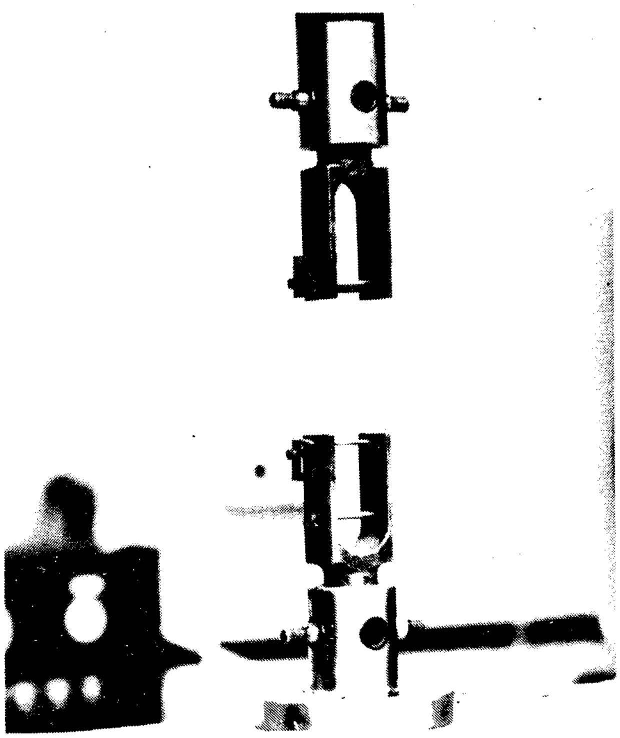
Figure 8. Test Specimen Cutter



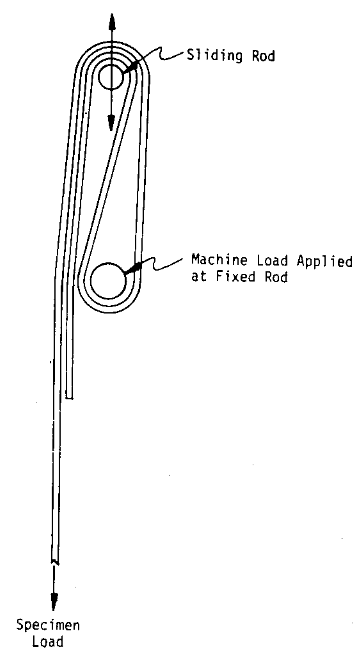
(a) Hydraulic



(b) Mechanical



(c) "D" Ring



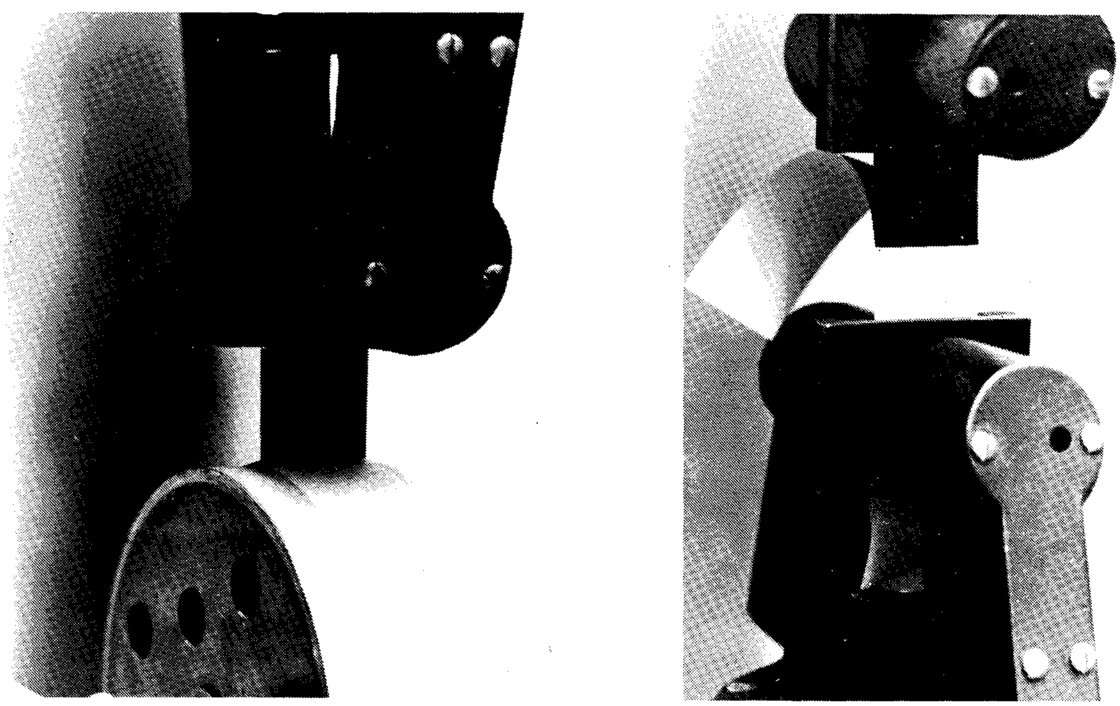
(d) Material Wrap for D-Ring
Jaws

Figure 9. Various Specimen Grips

Peel strength testing. - Peel strength measurements on film-to-fabric bonds were made in accordance with ASTM D 1876, Reference 4, Figure 10b. Film-to-film bonds were testing using Sheldahl peel test method Q000066, illustrated in Figure 10a. In the former, both adherends are allowed to flex about 90 degrees near the line of failure. The equilibrium flex angles vary depending on the relative stiffness of the adherends. No external control over the angle was exercised. Under Q000066, one adherend is flexed through 90° or less and the other through a very small angle, Figure 10a. Because of asymmetry in flexing, all film-to-film peels were made from the outer surface of the laminate by mounting the fabric side against the drum.

Film-fabric peels under D 1876 were run at 30.5 cm/min (12 in./min) and the film-to-film peels at 5.1 cm/min (2 in./min). Peel strength is rate sensitive and measurements made at different rates cannot generally be compared.

Five tests were conducted on each of the ten composites at 22°C (72°F). Laminated peel specimens were prepared by inserting release paper between plys at layers to facilitate testing by providing an initial free length for clamping. Control specimen peel was initiated by cutting with a razor blade.



(a) Sheldahl Q00066 (b) ASTM D 1876

Figure 10. Peel Strength Testing

Durability Tests

The custom experimental and control materials were exposed to handling and durability tests to measure characteristics essential to the performance of inflatable structures. These included measurement of crease, tear, and puncture resistance.

Crease effects. - Coupon samples were cut and folded parallel to the grips in accordian fashion with a 2.54-cm (1-in.) spacing between folds, Figure 11. Each fold was a 180° sharp crease. The coupons were then tested per Federal Test Method (FTM) 5102 to determine loss in strength. Five samples of each material were tested at 22°C (72°F).

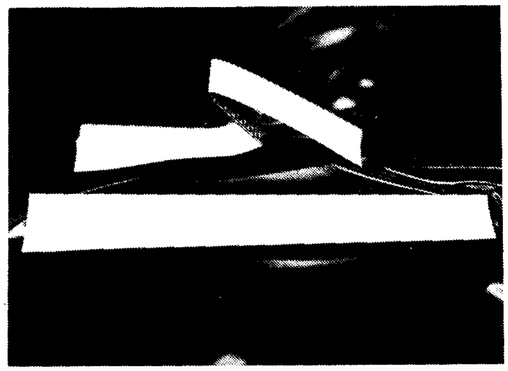
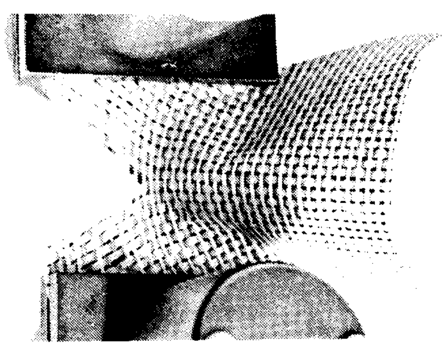
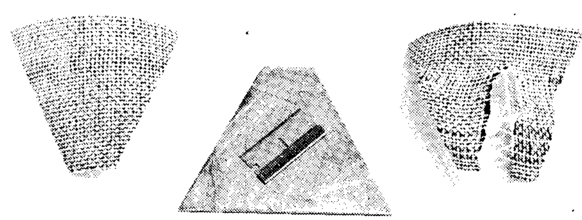


Figure 11. Folding Method for Crease Specimens

Trapezoidal tests. - FTM 5136 was used. Sample form is a right trapezoid 7.5 cm (3 in.) high with bases of 2.54 cm (1 in.) and 10.2 cm (4 in.) as shown in Figure 12. The test specimen was notched on the 2.54-cm base (1-in. base) and clamped with the two non-parallel edges gripped in the jaws as shown in Figure 12a. Grip separation rate was 30.5 cm/min (12 in./min). Five specimens of each material were tested at a temperature of 22°C (72°F). A standard template is shown in Figure 12b along with specimens before and after failure. The tear occurs normal to the warp yarns and generally a minimum tear force is noted along orthogonal tears. Composites with bias-fiber plys sustain much higher tear forces. Loose, woven uncoated fabrics show greater tear strength than impregnated and coated or close weave materials. This characteristic allows the designer to alter tear reistance without affecting tensile strength.



(a) Specimen Under Test



(b) Test Specimens - Before and After Testing

Figure 12. Trapezoidal Tear Testing

Puncture tests. - Sheldahl Industrial Specification Q000215 was used. Under this method, a 15-cm (6-in.) diaphragm of material is pressurized with air to about one-third the material's ultimate stress (Figure 13a). A stylus (Figure 13b) is pressed against the material and the stylus force at which puncture occurs is taken as a relative measure of puncture resistance. Where sample material was limited, an alternate method was employed using a coupon clamped across a 1.1-cm (0.43-in.) diameter hole (Figure 13c), and the same jig and stylus.

The principal difference between the two methods is presence of tensile stress in the material under Q000215. Puncture of flaccid material (Figure 13c) simulates damage occurring to the material during fabrication and handling, and the stressed-material puncture simulates damage to a pressurized inflatable structure.

Five tests on each material were conducted at a temperature of 22°C (72°F) with the stylus initially applied from the Tedlar or Hypalon side.

Handle Tests

For flexible, inflatable structures, material feasibility is highly dependent on its capacity to sustain multiple packaging cycles at high packing densities, to accommodate simple or compound folding, and to adapt to compound curvatures without damage to the gas barrier. This characteristic can be measured in a relative way with a "handle" test.

The handle property concept and a method for measuring it have been developed at the NASA Langley Research Center (Reference 5). The method consists of measuring the slope of the force displacement data acquired from extraction of a circular specimen through a nozzle, Figure 14. It was postulated and proven by test that lateral pressures in the nozzle during initial extraction are proportional to the local packing density of the compacted material times a material constant. The axial component of the integral of the pressure and associated friction forces over the nozzle surface are equated to the extraction force, *F*. This provides a means for determining an intrinsic material constant, termed the handle modulus, *H:*

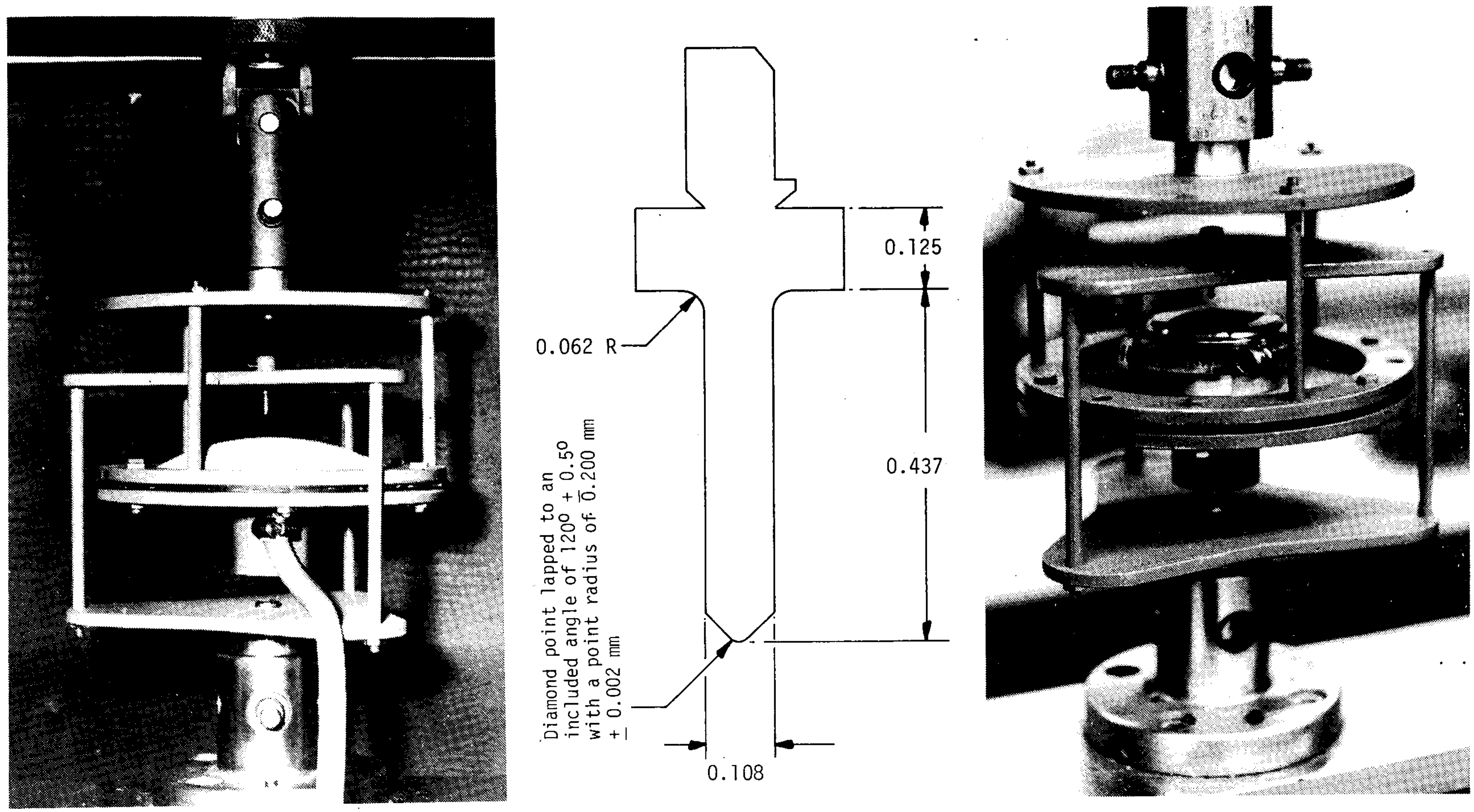
$$H = \frac{1}{A_o N} \frac{dF}{dP_o}$$

where A_o is the orifice area

$\frac{dF}{dP_o}$ is the variation of the extraction force with respect to a variation in the packing ratio at the nozzle throat;

N is a characteristic number of the nozzle geometry;

P_o is the ratio of the differential volume occupied by the compacted specimen to the volume of a differential slice through the nozzle normal to the axis of revolution.



(a) (b) (c)

Figure 13. Puncture Test Equipment

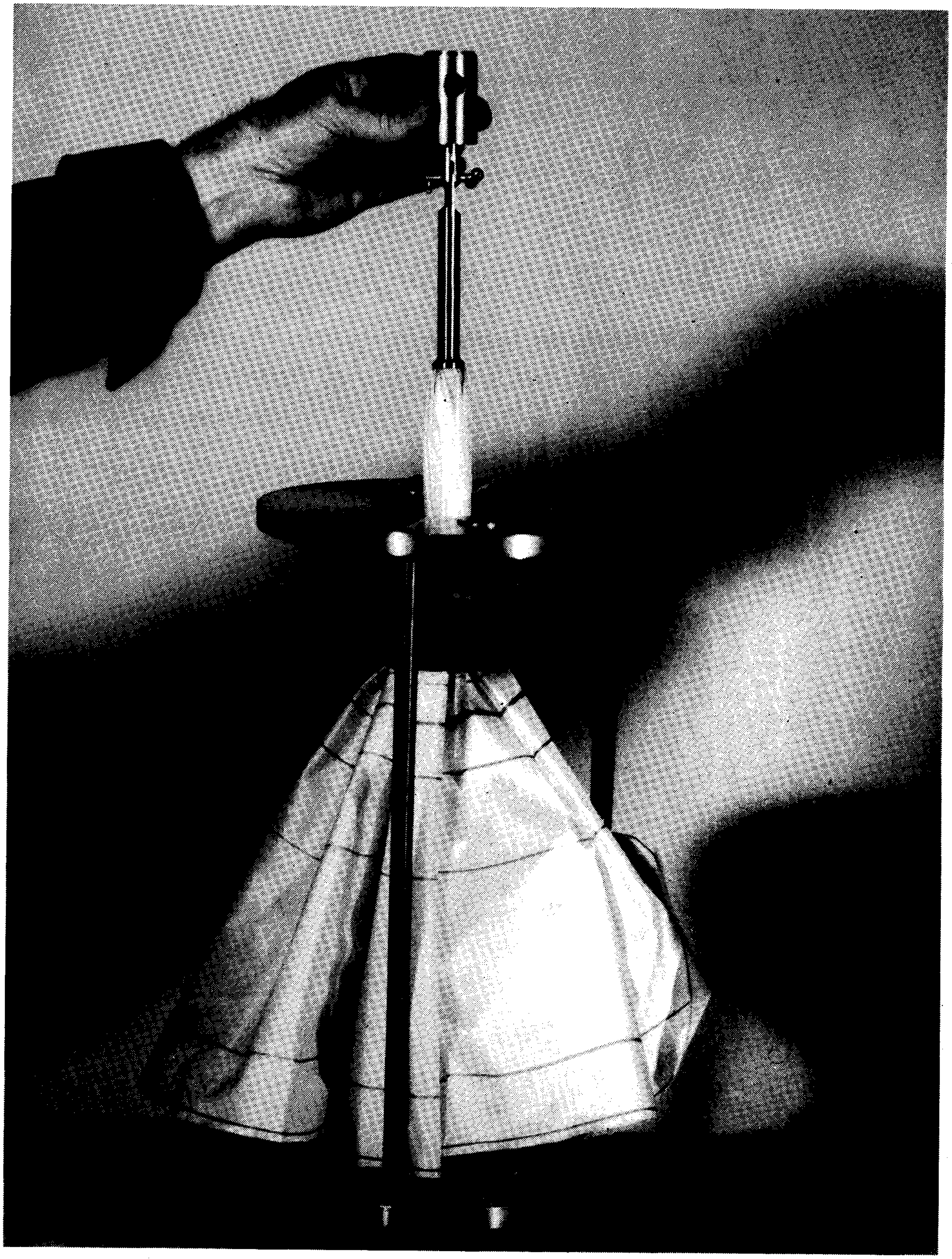
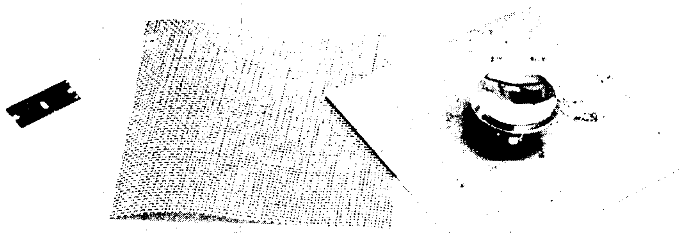


Figure 14. Handle Test Apparatus

Geometric Properties

Weight measurements. - Weight measurements were made by cutting a 15.2-cm by 15.2 cm (6-in. by 6-in.) sample of each control and each custom material and weighing on a precision laboratory balance.

The cutting template and a specimen are shown in Figure 15a and the laboratory balance in Figure 15b.



Weight sample, oz/yd^2

6-in. by 6-in. template

(a) Sample Template and Preparation

(b) Laboratory Balance

Figure 15. Weight Measurement

TEST RESULTS AND DISCUSSION

Strength data were obtained by unaxial testing and by peel testing. Durability data acquired included crease effects, tear strength and puncture resistance. Additional information on durability and geometric properties is given in Reference 3. The tests of Reference 3 were conducted for materials, produced on full-scale production machinery, while the similar materials 1a, 1b, and 5a of this study were custom-made by hand.

Uniaxial Tensile Test Results

Uniaxial testing is simple, fast, and inexpensive; it is adequate as an indication of relative strength and anistopy and as a quality control procedure. However, uniaxial tests are not generally a reliable indication of strength for film and fabric composites having diagonal structural elements. For such materials, the appropriate equilibrium forces are lacking at the free edges which affects the contribution of diagonal and transverse fiber constituents and degrades the weave, crimp, and yarn interlocks. The failure of uniaxial coupon tests to fully involve these structural features of laminated fabric materials has motivated more sophisticated biaxial testing using cylindrical specimens, described in References 1 and 3. In the tests described here, coupon tests involved two distinctly different structural mechanisms for specimens tested along the bias and for specimens tested along the machine and transverse directions. The temperature response of the two types of test specimens suggests some basic principles of fabrication, adhesion, test methods and temperature dependency useful in future material designs.

For orthogonally aligned specimens (MD and TD) having no bias yarns, the fabric constituents aligned with the specimen axis are loaded directly without being significantly affected by the bond strength, degree of encapsulation, and free boundary forces which strongly affect bias-direction tests.

In this program the changes in stress and strain that occur with temperature for the orthogonal and bias specimens of various fabrications vary widely but are consistent with the specimen type, constituents, and fabrication details. This is not readily evident because of the eight different combinations of test directions and materials.

These combinations result in distinctly different temperature responses, in part as a result of the thermomechanical behavior of the adhesive, common to all the materials. The thermomechanical behavior of this adhesive is reported in Reference 6 from which the thermomechanical spectra in Figure 16 were obtained. The adhesive exhibits onset of glasseous-phase transition at -10°C and a second glasseous transition at -40°C. The rigidity of the adhesive increases 560 percent between the 22°C room temperature and the -51°C cold temperature test environment. Adhesive in the cold state improves integration of the films and fabrics by reducing edge losses

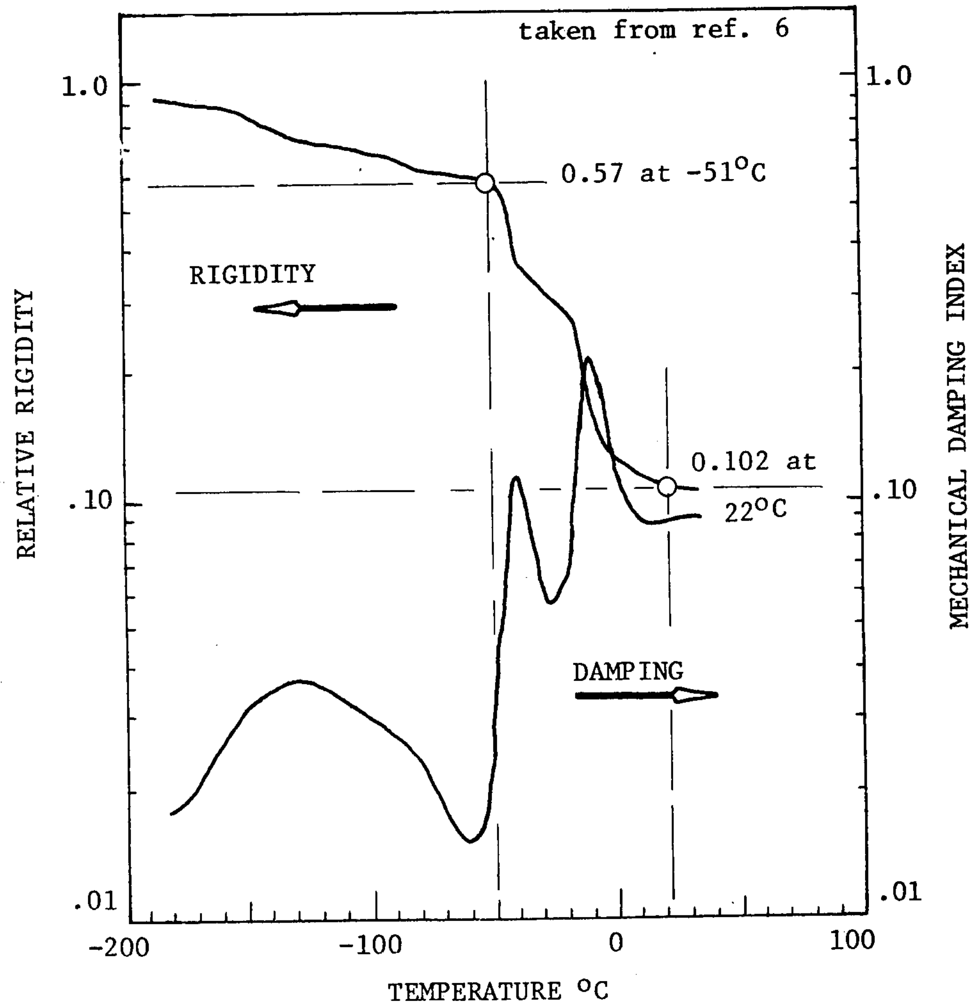


Figure 16. Thermomechanical Spectra of Adhesive

and interlaminar shear deformation, by better constraining crimp and weave interlocks and by decreasing the difference between elastic moduli of film and adhesive layers.

The contribution of diagonal reinforcement in narrow, uniaxially loaded specimens depends on the Poisson's ratio of the films, the tensile and compressive elastic moduli of the films and adhesives, the tensile modulus of the yarn, the twist, crimp, angle of diagonal orientation, and the location of constituents normal to the specimen plane. The contribution of diagonal fibers for bias-direction tests is appreciably different for Kevlar and Dacron. The rheological factors cited are not as important for tensile strength of specimens loaded along machine and transverse directions.

Though hardening of a composite-materials matrix can have favorable effects on strength and stiffness, opposing effects also occur. Increased ridigity is accompanied by a loss in the composite's capacity to yield and adapt to unequal load distribution and stress concentrations. The constituent

materials, the test orientation, and the temperature determine whether or not low temperature advantages exceed the disadvantages.

Coupon tensile strength data are provided in TABLE 4 for the ten material types. Data are for the load and sample orientations along the machine direction (MD), transverse direction (TD), 45° to the left, and right of the MD. Tests were performed at room temperature, 22°C (72°F) and at the usual environmental extremes for inflatable structures, -51°C (-60°F) and 60°C (140°F). The data are compared graphically in Figures 17 and 18. Data on elongation at failure for the same conditions are provided in TABLE 5 and Figures 19 and 20. Figure 21 shows failure patterns representative of specimens 2c, 4c, and 6c having a bias-yarn array. Careful study of the strength data shows that all Kevlar materials show significant improvement over their Dacron controls along the warp and fill, and moderate or varying improvements along diagonal axes.

The strength data of Figures 17 and 18 and the strain data of Figures 19 and 20 show several trends with temperature, material construction, and specimen orientation. MD and TD tests of Kevlar materials with Dacron-bias fabric (5b and 6b), show constant or increased strain with decreased strength for a temperature change from +22°C to -51°C. The corresponding control material having all Dacron reinforcement (5a) shows nearly constant strength, but decreasing strain with temperature drop.

The Kevlar materials with no bias reinforcement, 1b, 2b, and 3b, show consistent loss in strength and increase in strain for the MD and TD tests as temperature is reduced below ambient. However, the same materials tested in the bias direction generally show strength increases and strain decreases as temperature drops. The MD and TD tests of materials having Kevlar bias-yarn arrays (2c, 4c, and 6c) behave similar to the MD and TD tests of specimens 1b, 2b, and 3b but show a difference in the bias specimens of no loss to moderate loss in strength and decrease in strain to temperature drop.

The all-Dacron control materials perform differently from their Kevlar counterparts. Laminate 1z shows increasing strength with increasing strain for the orthogonal specimens and near-constant stress with decreasing strain for the bias specimens. The all-Dacron coated material, 5a, shows constant strength with decreasing strain for the orthogonal specimens and similar behavior for the bias specimens.

Explanations for these eight characteristic modes of behavior are suggested in the following sections.

TABLE 4. - Tensile Properties at Failure

Material Code*	Test Direction	60°C (140°F) N/m (lb/in.)	60°C (140°F) C.V.**	22°C (72°F) N/m (lb/in.)	22°C (72°F) C.V.**	-51°C (-60°F) N/m (lb/in.)	-51°C (-60°F) C.V.**
1a	MD	3.87×10^4 (221)	0.065	4.24×10^4 (242)	0.053	5.36×10^4 (306)	0.035
	TD	3.24 (185)	0.094	4.02 (229)	0.067	5.49 (313)	0.142
	45°L	1.52 (87)	0.065	2.23 (128)	0.046	2.34 (133)	0.103
	45°R	1.00 (57)	0.103	2.02 (115)	0.077	1.68 (96)	0.129
1b	MD	5.57 (318)	0.151	5.49 (314)	0.066	4.72 (269)	0.218
	TD	6.25 (357)	0.127	5.58 (318)	0.088	3.91 (223)	0.354
	45°L	2.28 (130)	0.201	3.12 (178)	0.207	3.21 (183)	0.070
	45°R	2.54 (145)	0.049	2.90 (166)	0.057	3.78 (216)	0.227
2b	MD	5.92 (338)	0.051	5.55 (316)	0.121	3.51 (200)	0.318
	TD	5.85 (334)	0.117	4.82 (275)	0.153	3.62 (207)	0.243
	45°L	2.71 (155)	0.079	3.38 (193)	0.181	3.00 (172)	0.088
	45°R	2.64 (151)	0.113	3.16 (180)	0.030	3.09 (176)	0.301
2c	MD	5.58 (319)	0.023	5.65 (323)	0.048	4.48 (256)	0.098
	TD	6.83 (390)	0.040	6.00 (343)	0.067	4.46 (255)	0.240
	45°L	2.18 (125)	0.029	2.64 (151)	0.262	2.11 (121)	0.061
	45°R	2.21 (126)	0.248	2.73 (156)	0.139	2.46 (140)	0.126
3b	MD	5.80 (331)	0.142	5.87 (335)	0.029	4.52 (258)	0.180
	TD	5.76 (329)	0.045	5.35 (306)	0.091	5.49 (314)	0.199
	45°L	2.58 (148)	0.147	3.51 (200)	0.096	4.21 (240)	0.087
	45°R	2.62×10^4 (150)	0.192	3.79×10^4 (217)	0.039	4.60×10^4 (263)	0.043

*See Figure 2 for definition of material matrix - row number, column letter.
**C.V. = coefficient of variation.

TABLE 4. - Tensile Properties at Failure (Concluded)

Material Code*	Test Direction	60°C (140°F) N/m (lb/in.)	60°C (140°F) C.V.**	22°C (72°F) N/m (lb/in.)	22°C (72°F) C.V.**	-51°C (-60°F) N/m (lb/in.)	-51°C (-60°F) C.V.**
4c	MD	5.27×10^4 (301)	0.066	5.45×10^4 (311)	0.036	3.93×10^4 (224)	0.200
	TD	5.89 (337)	0.058	4.39 (250)	0.030	4.50 (257)	0.336
	45°L	1.83 (105)	0.110	3.05 (174)	0.129	2.84 (162)	0.072
	45°R	1.76 (100	0.090	2.63 (150)	0.129	2.29 (131)	0.050
5a	MD	3.61 (206)	0.021	3.72 (213)	0.022	3.83 (219)	0.184
	TD	3.21 (184)	0.017	3.45 (197)	0.044	3.02 (172)	0.052
	45°L	2.39 (137)	0.089	3.23 (185)	0.026	2.81 (160)	0.152
	45°R	2.17 (124)	0.035	2.42 (138)	0.029	2.53 (145)	0.163
5b	MD	5.86 (335)	0.072	6.64 (379)	0.042	5.61 (320)	0.204
	TD	5.31 (304)	0.089	6.91 (395)	0.043	6.14 (351)	0.194
	45°L	3.28 (187)	0.071	4.44 (254)	0.026	3.36 (192)	0.205
	45°R	3.20 (183)	0.099	4.98 (285)	0.041	3.68 (210)	0.175
6b	MD	5.94 (339)	0.094	6.52 (373)	0.052	5.15 (294)	0.191
	TD	6.34 (362)	0.090	8.02 (458)	0.048	6.65 (380)	0.116
	45°L	4.12 (235)	0.071	5.11 (292)	0.062	6.60 (377)	0.085
	45°R	4.26 (243)	0.094	5.83 (333)	0.037	6.01 (343)	0.165
6c	MD	5.83 (333)	0.127	5.71 (326)	0.085	5.42 (310)	0.222
	TD	6.64 (379)	0.067	5.75 (328)	0.061	4.37 (250)	0.158
	45°L	2.46 (140)	0.030	4.51 (258)	0.054	4.39 (251)	0.162
	45°R	3.12×10^4 (178)	0.114	4.76×10^4 (272)	0.131	4.66×10^4 (266)	0.087

*See Figure 2 for definition of material matrix - row number, column letter.
**C.V. = coefficient of variation.

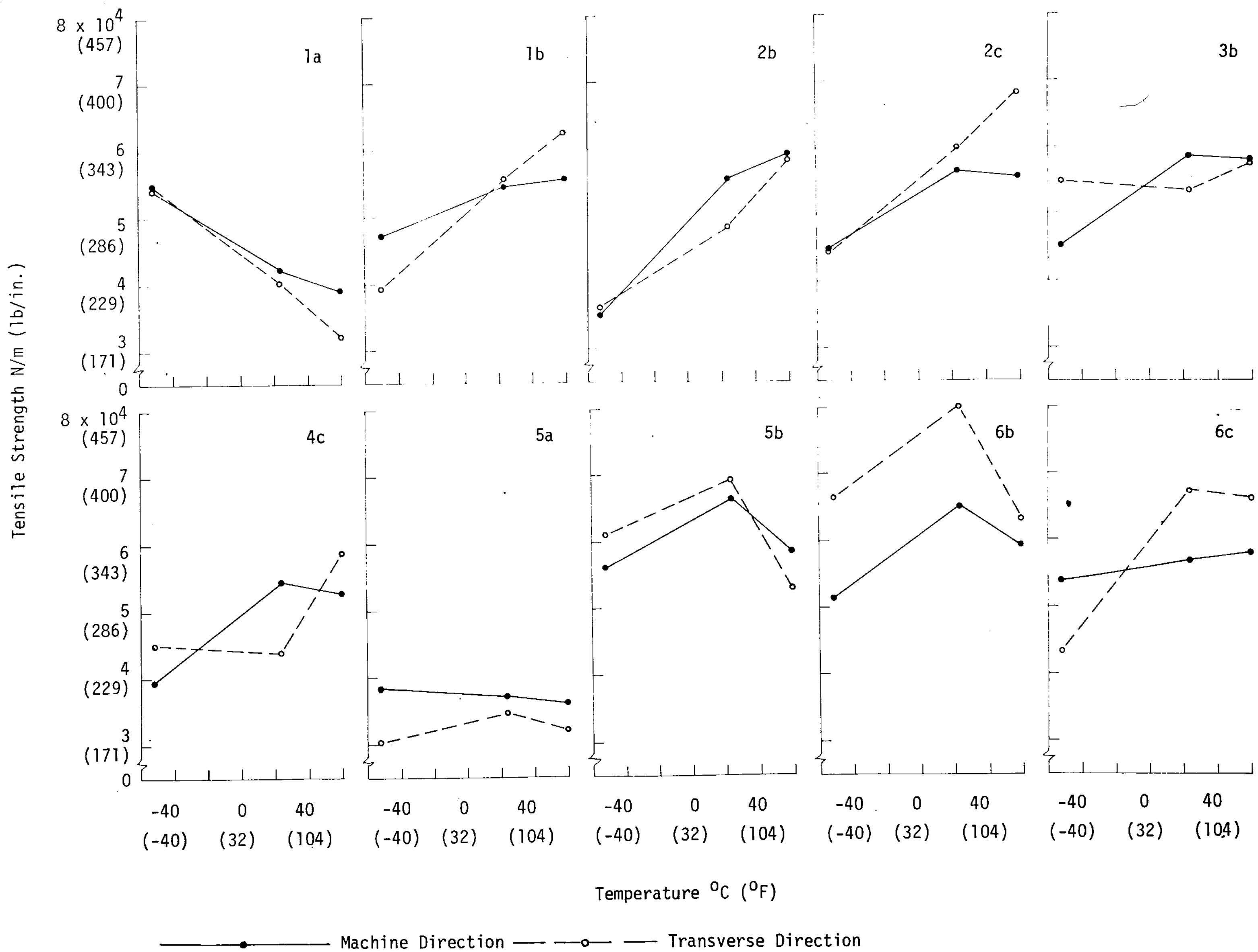


Figure 17. Variation of Tensile Strength at Failure with Temperature

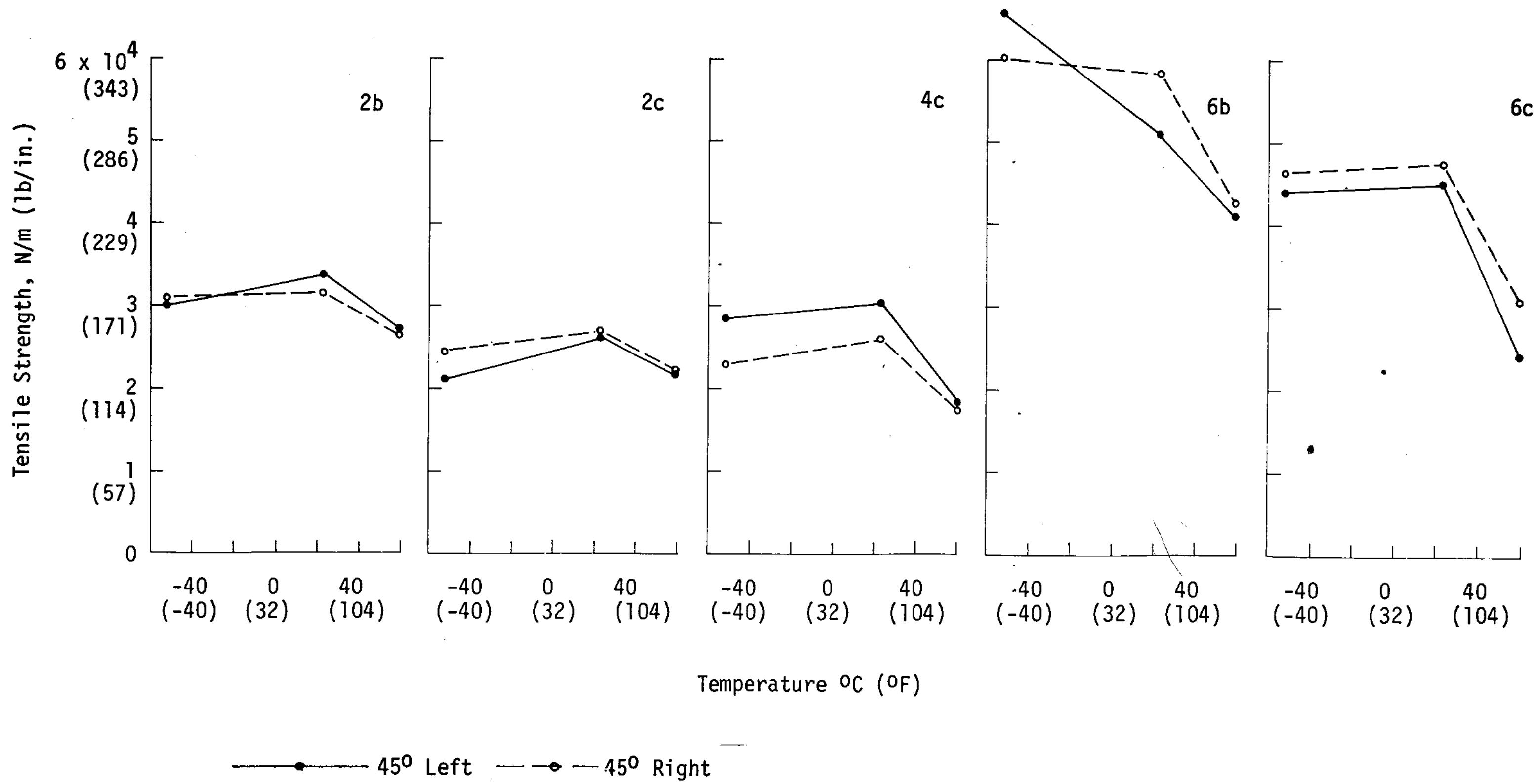


Figure 18. Variation of Tensile Strength with Temperature

TABLE 5. - Tensile Elongation at Failure

Material Code*	Test Direction	60°C (140°F)		22°C (72°F)		-51°C (-60°F)	
		Percent	C.V.**	Percent	C.V.**	Percent	C.V.**
1a	MD	19.8	0.039	16.0	0.053	25.4	0.126
	TD	16.4	0.071	14.8	0.085	24.6	0.247
	45°L	51.8	0.043	47.7	0.077	21.2	0.361
	45°R	38.0	0.142	50.9	0.039	15.0	0.125
1b	MD	5.9	0.047	4.0	0.000	10.0	0.071
	TD	5.4	0.119	4.4	0.064	10.7	0.206
	45°L	37.8	0.059	48.1	0.108	38.0	0.157
	45°R	45.6	0.062	38.6	0.105	32.0	0.337
2b	MD	5.3	0.062	4.8	0.116	7.2	0.267
	TD	5.2	0.097	4.5	0.066	6.6	0.254
	45°L	42.6	0.101	38.7	0.109	23.2	0.239
	45°R	41.2	0.090	32.5	0.077	20.5	0.129
2c	MD	5.9	0.061	5.3	0.000	8.2	0.054
	TD	5.7	0.049	5.4	0.053	10.6	0.143
	45°L	47.3	0.022	43.3	0.044	12.4	0.354
	45°R	43.8	0.153	49.3	0.163	20.0	0.359
3b	MD	5.4	0.101	5.1	0.058	8.6	0.335
	TD	5.3	0.053	4.1	0.122	8.4	0.180
	45°L	45.7	0.057	45.7	0.063	36.8	0.070
	45°R	46.7	0.105	42.6	0.064	36.4	0.227
4c	MD	5.5	0.069	4.3	0.000	12.0	0.144
	TD	5.5	0.033	5.0	0.019	11.8	0.163
	45°L	53.9	0.104	36.3	0.026	13.2	0.196
	45°R	49.2	0.154	52.5	0.207	12.4	0.072
5a	MD	25.7	0.018	26.3	0.050	21.0	0.177
	TD	32.5	0.027	32.0	0.059	23.3	0.243
	45°L	63.5	0.103	71.9	0.051	15.9	0.391
	45°R	60.9	0.091	66.9	0.012	12.8	0.236
5b	MD	8.1	0.064	8.5	0.127	11.3	0.288
	TD	7.3	0.053	5.8	0.062	10.6	0.108
	45°L	65.2	0.050	61.4	0.028	19.3	0.393
	45°R	68.6	0.022	54.2	0.093	29.1	0.262

*See Figure 2 for definition of material matrix - row number, column letter.
**C.V. = coefficient of variation.

TABLE 5. - Tensile Elongation at Failure (Concluded)

Material Code*	Test Direction	60°C (140°F)		22°C (72°F)		-51°C (-60°F)	
		Percent	C.V.**	Percent	C.V.**	Percent	C.V.**
6b	MD	10.0	0.192	9.2	0.142	7.6	0.379
	TD	8.4	0.138	7.6	0.072	8.0	0.200
	45°L	59.6	0.122	64.0	0.022	62.8	0.087
	45°R	60.0	0.074	63.8	0.017	42.4	0.182
6c	MD	7.9	0.046	5.9	0.082	5.7	0.168
	TD	5.5	0.054	4.3	0.104	4.4	0.110
	45°L	46.0	0.048	58.9	0.044	36.2	0.074
	45°R	34.4	0.079	45.0	0.063	18.5	0.391

*See Figure 2 for definition of material matrix - row number, column letter.
** C.V. = coefficient of variation.

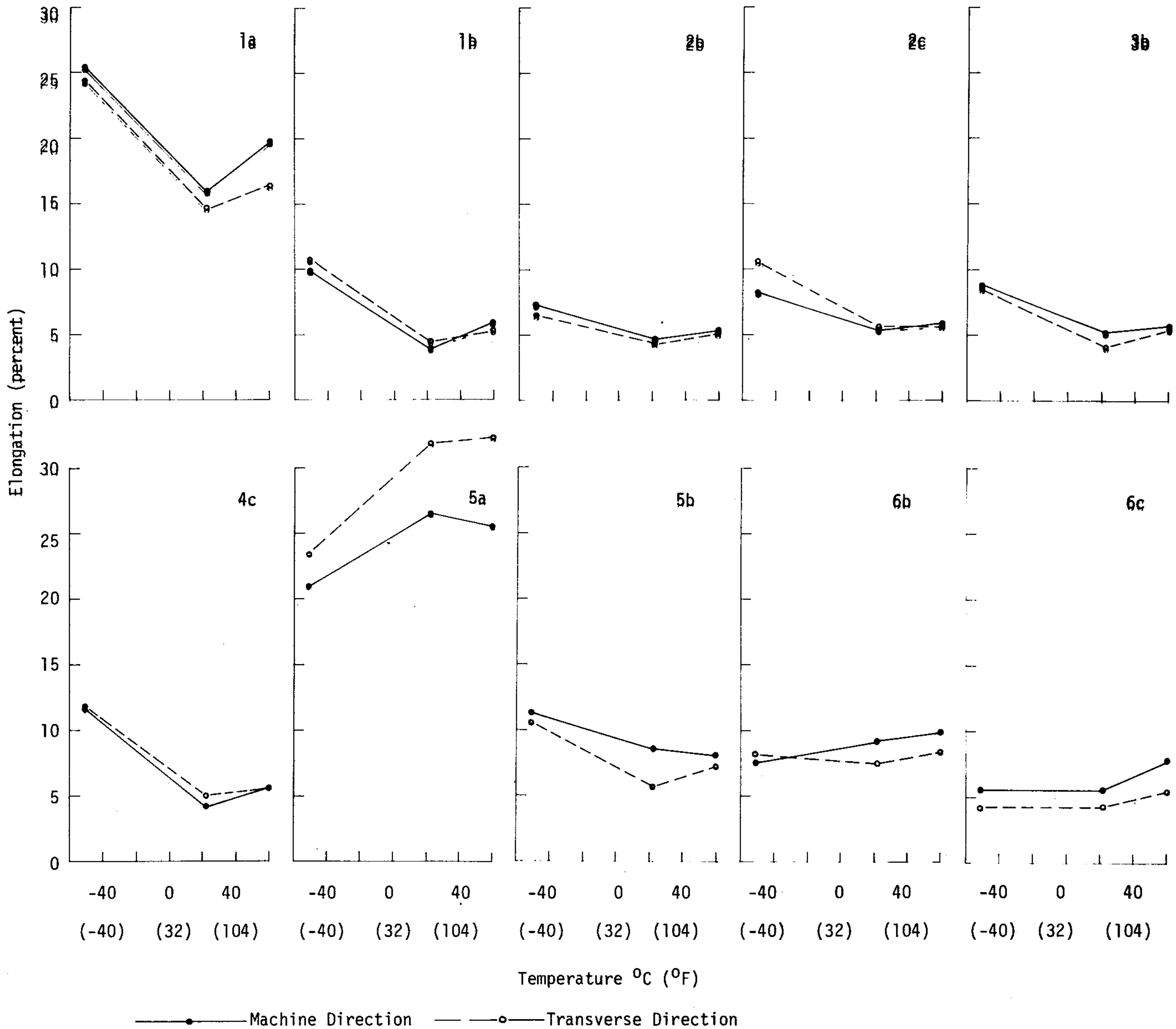


Figure 19. Variation of Elongation at Failure with Temperature

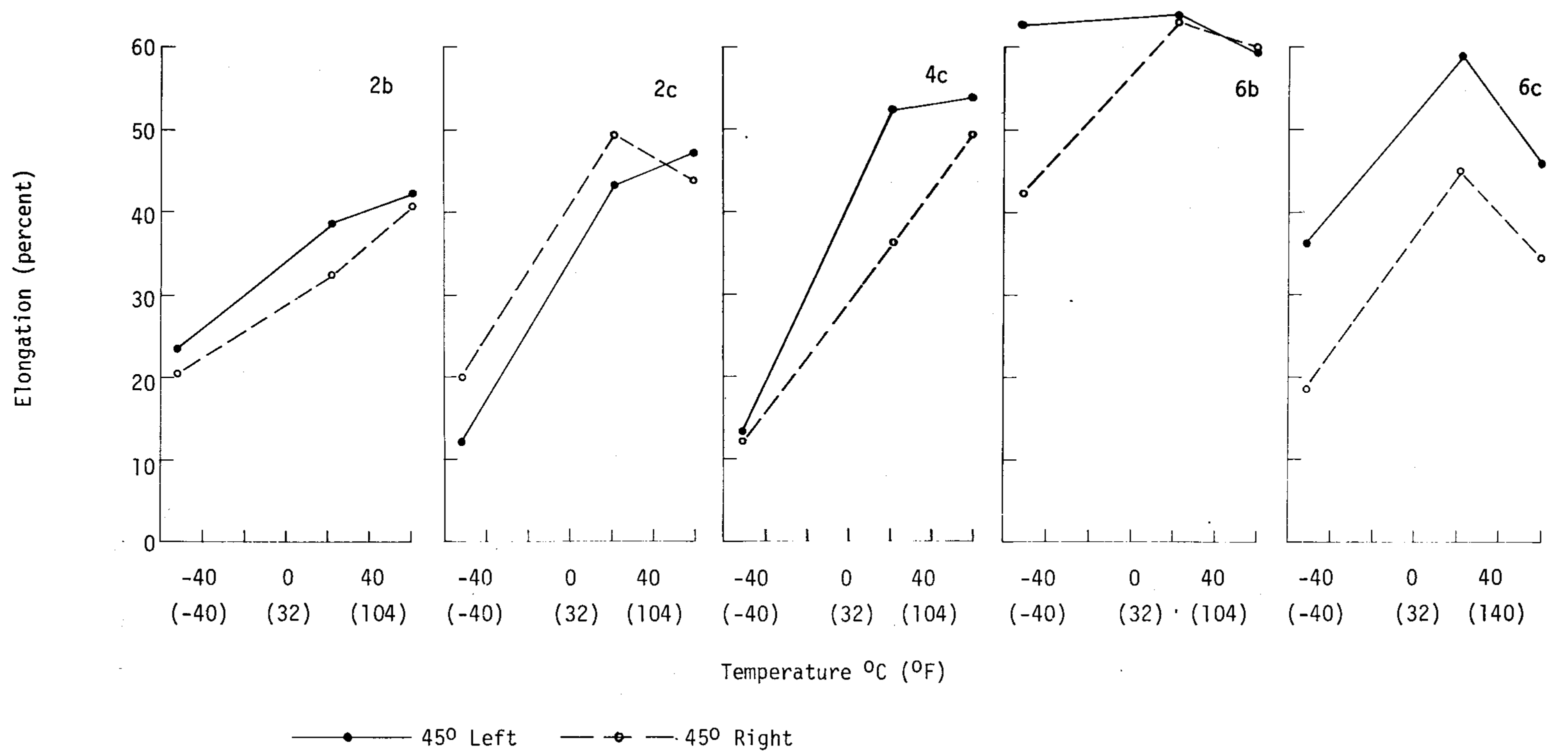
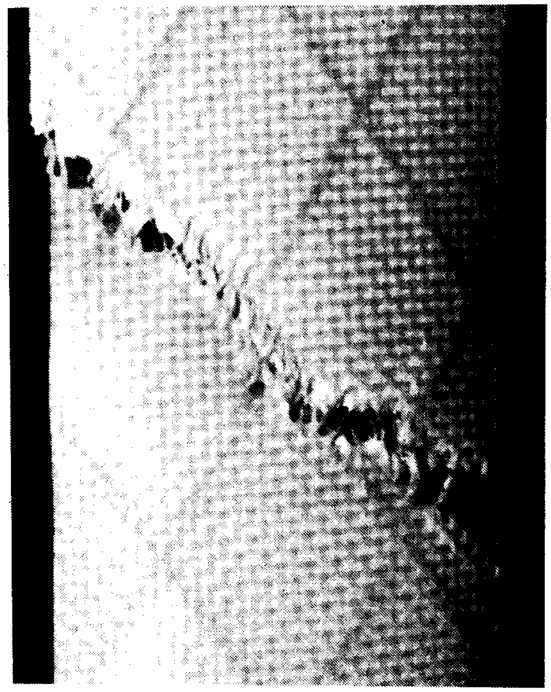
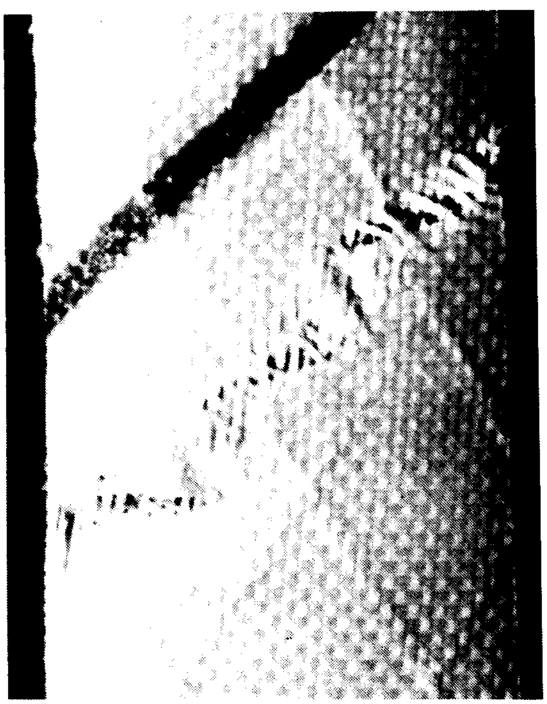


Figure 20. Variation of Elongation with Temperature

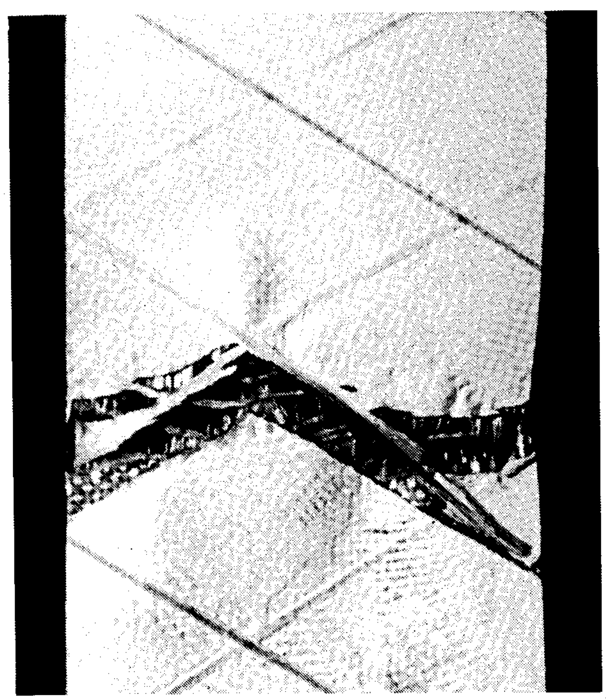
(a) Material 2c, MD Load



(b) Material 2c, TD Load



(c) Material 2c, TD Load



(d) Material 6c MD Load

Figure 21. Representative Failure Patterns of Materials Having a Bias-Yarn Array

Dacron control laminate 1a. - This material exhibits the large elongations characteristic of Dacron and Mylar. The MD and TD elongations are representative of plain-weave Dacron fabrics. The bias elongations are representative of Mylar and adhesive strains since this material has no bias reinforcement.

For a drop in temperature from 22°C to -51°C the stress and elongation for the MD and TD tests show characteristic increases. Although the constituent stiffnesses increase in the cold environment, the similarity of film and yarn elastic moduli and the more rigid bonds between them results in a relative strength increase with temperature greater than the change in stiffness

For the bias-test direction, a reduction in elongation and little strength change is observed with the drop in temperature. This may be partially attributed to the increased stiffness of the Mylar and adhesive, but is primarily attributed to the increased contribution of Dacron fabric diagonal to the test direction caused by increased adhesive rigidity (phase change). In spite of the increased diagonal yarn contribution, there is little net increase in strength. Strength and elongation results may be inconclusive, however. Small triangular regions, which occur where diagonal yarns are fixed by the test grips, produce a non-uniform stress field across the width of the coupon and cause the actual strain along the specimen's centerline to be greater than the indicated strain. Average strains in TABLE 5 are thought to be less than the true local strain associated with failure. The average strengths in TABLE 4 for bias-direction tests are thought to be less than the membrane forces at the apexes of the triangular areas at the specimen ends. In addition, the adhesive bonds have greater sensitivity to the disruptions in the stress field because of reduced adhesive toughness at temperatures below the glass transitions.

Kevlar-based laminates 1b, 2b, and 3b. - These materials are similar to the control 1a except that Kevlar is used in place of Dacron. The lower elongations exhibited by MD and TD tests of 1b, 2b, and 3b compared to 1a are a direct result of the high modulus Kevlar fabric. A reduction in elongation was not observed in the bias direction, indicating that the Kevlar did not fully contribute to composite stiffness in that direction because of the free fabric edges in the narrow bias specimens.

Of particular interest is that the temperature effect on strength and strain from 22°C to -51°C is opposite to that of the control, 1a. MD and TD elongations at -51°C are consistently greater than at 22°C, but the amount of change varies widely. The larger strains at -51°C are about twice the ultimate strain characteristic of Kevlar. There is an average 25-percent reduction in strength between 22°C and -51°C which is opposite to the strength changes that occur in the constituents tested separately. The yarn load distribution for the MD and TD tests was probably quite uniform. In view of the above, it was concluded that the strength reduction and strain increase must be attributed to partial filament bond failure and reduced toughness resulting from the thermomechanical phase change in the adhesive. This low ductility becomes particularly apparent in composites with high strength, high modulus Kevlar yarns. Internal random bond failure probably

occurs without external appearance of failure until general specimen rupture takes place below the potential strength of the constituents.

At 22°C the MD and TD strength is greater and the strain is within the possible range for Kevlar, considering crimp and weave effects. This suggests that the Kevlar must be contributing more to the strength because of greater adhesive deformability and toughness.

The net effect of adhesive phase change and embrittlement is detrimental for MD and TD test orientations of high modulus materials. Conversely, the net effect appears beneficial for the Dacron material, 1a. Materials 1b, 2b, and 3b have no bias reinforcement and depend on the film for shear strength. Bias strengths of the Kevlar laminates are considerably improved over the Dacron control laminate. This can only be attributed to load transfer between the film and yarns, in spite of the free yarn ends; 1b and 3b show particularly enhanced bias strengths in the cold environment. The 2b material has less sensitivity to temperature, similar to the control 1a. Note that bias elongations are well in excess of those characteristic of Kevlar fabrics and that widespread yarn-bond failure probably occurred along with yarn strain, crimp reduction and lateral specimen contraction. It is possible that the composite was sufficiently integrated despite yarn-bond failures to show stiffness gains exceeding the stiffness of Dacron control and film constituents. Local strains are suspected to be greater than the average indicated because some of the yarn ends are restrained in the specimen grips. The discussion of specimen 1a bias loading is generally applicable to 1b, 2b, and 3b except that the Kevlar is thought to contribute more strength than the Dacron within the threshold of bond integrity. In addition, the yarn-bond strength is more likely to determine the composite failure points for Kevlar materials which appear to occur at stress levels considerably higher than for the Dacron control. The increase in adhesive stiffness with low temperatures contributes to the cold temperature, bias-direction performance of the Kevlar materials.

Materials with Kevlar-based fabric and Kevlar-bias yarns. - Materials 2c, 4c, and 6c have an orthogonal base fabric of Kevlar and a bias Kevlar reinforcement. The effect of the bias reinforcement on specimens 2c, 4c, and 6c is totally obscured by the lack of equilibrium boundary forces at the free edge of specimens. For tests in the MD and TD directions, the discontinuous bias yarns to not contribute directly as a load-carrying constituent. For bias-direction tests, only about one yarn of the sparse array, Figure 5a, has continuity between grips. The high ultimate strains exhibited for bias-direction loads were five to six times the characteristic breaking strain of Kevlar, assuring that the bias yarn aligned with the test direction must have broken or debonded from the matrix at some lower stress level. Bias-direction tests were probably not satisfactory indicators of the Kevlar-bias yarn strength. The discussions of materials 1b, 2b, and 3b above generally apply to 2c and 4c because of their similarity, except for the Kevlar-bias yarns. There is evidence from the bias-strength tests that low temperature performance is impaired by the Kevlar-bias yarns. Asymmetry of the Kevlar-bias ply with respect to the neutral plane is thought to reduce the contribution of this constituent.

Strains in 2c, 4c, and 6c are greatly decreased from 22°C to -51°C. This cannot be attributed to the increases in elastic modulus of the structural fabric at low temperatures which is about 20 percent, nor to the small modulus change of Kevlar. It appears that the increase in stiffness is caused by the adhesive phase transition which increases the contribution of the Kevlar base fabric, oriented diagonal to the bias test direction.

Bias-direction stiffness is dramatically improved by increasing the contribution of the base fabric through a more rigid bond. The bias yarns do not increase significantly in stiffness because of the large yarn separation. Tensile strength is not appreciably altered from the room-temperature performance. This is attributed to the large differences in stiffness between the film, adhesive, and Kevlar. At low temperatures, initially, loads are carried primarily by the Kevlar which is bonded to the film by the glasseous adhesive. The adhesive shear strength limit is reached before the Kevlar tensile limits, causing bond failure and slippage which cause the composite to perform as at high temperature, with several differences. Since yarn-bond failures probably don't occur simultaneously, only local regions experience transfer of loads from the Kevlar to Mylar. The ensuing composite failure is observed at average elongations above the Kevlar limits but consdierably below the break strain characteristic of Mylar.

The observed bias strengths of materials 2c and 4c do not reflect the conbtibution of the Kevlar-bias reinforcement. Their strengths are similar to materials 2b and 3b because of inadequacies of the coupon tests.

Specimen 4c is geometrically similar to material 2c except for the substitution of a bi-laminate of Hytrel and Saran for the Mylar film. The test data indicate no conclusive differences in strength and elongation at the temperatures investigated.

For the MD and TD tests, the coated material 6c differs from the laminates (2c and 4c) in the respect that strain is essentially unchanged from 22°C to -51°C. It is similar to the other materials in strength, showing a drop in MD and TD strength with temperature. Break strains of the 6c MD and TD direction tests are compatible with Kevlar fabric strains, indicating full contribution of the Kevlar throughout the temperature range. The reduction in strength with temperature is an indication of the inability of the coating-yarn bonds to maintain composite integrity up to the breaking strength of the Kevlar. Generally, coated materials give better yarn bonds than laminates because the greater amount of coating matrix required to control permeability surrounds the yarns more completely and increases the bond area.

The 6c coated Kevlar-bias yarns show bias-direction strain characteristics very similar to materials 2c and 4d. The arguments above for the reduced Kevlar-bias performance of 2c and 4c are generally valid for 6c. The insensitivity of bias strength to temperature is attributed to the nearly total ineffectiveness of the Kevlar-bias ply, and the effective load transfer to the base fabric yarns. The absolute bias strength of 6c is considerably

higher than for the laminates, indicating bias strength is very dependent on the amount of matrix which imbeds the yarn. The 6c material is not affected by the adhesive phase change, as is apparently the case for most of the laminates.

All of the "a" and "c" series materials as well as 5b, exhibit lower diagonal strengths compared to the MD and TD direction. The "a" series is totally Dacron-reinforced, explaining their lower strength compared to similar Kevlar materials. The 5b coated specimen shows relatively weak diagonal strength, attributed to the large difference in strength between the Dacron bias fabric and the Kevlar base fabric with yarns aligned with the MD and TD. These indications of anisotrophy might be overly emphasized by virtue of the deficiencies in bias testing described in the preceding text.

Bias-fabric-reinforced materials. - Specimen 5a is the coated control, having a Dacron fabric aligned with the MD and TD axes and another Dacron fabric on the bias. The strength of the control is less along the bias than along the MD and TD because of the difference in weight of the two fabrics.

The strength is nearly independent of temperature for all test directions from 22°C to -51°C. This is attributed to the fact that the coated materials contain less of the adhesive believed to have pronounced thermomechanical effects on the laminates. Materials 5a, 5b, and 6b had a light wash coat of adhesive applied to the fabric for sizing purposes. Structural load transfer between yarns in the coated materials depends on the polyurethane and neoprene coatings. Yarn-to-coating bonds are not as temperature sensitive as the yarn-to-adhesive bonds and they are not as strong. For the 1a Dacron-fabric specimens the yarn bond shear strengths are reasonably well matched to the Dacron tensile capacity.

The temperature independence does not hold for the bias tests of material 5a. Increased stiffness appears for reduction in temperature from 22°C to -51°C. This is attributed to changes in moduli of the polyurethane, neoprene, and adhesive wash coat. The increased constituent stiffness probably increases the strength contribution of the yarns aligned 45° to the test direction. Materials having two fabric plys at 45° are thought to be less sensitive to load direction and to respond positively to stiffness increases of the matrix constituents. These probably cause the reduced bias strain observed. Although the coatings encapsulate the yarns more completely than the adhesives used in the laminated materials, yarn bonds to the polyurethane and neoprene are insufficient to improve matrix strength.

The extremely high elongations (up to 70 percent) for the bias tests of 5a, 5b, and 6b at 22°C and 60°C are much larger than characteristic Dacron filament break elongations. For the bias-test direction, one Dacron fabric ply is parallel and normal to the load axis. The large elongations may be attributed to yarn crimp removal, yarn untwisting, deformation and failure of the polyurethane- and neoprene-yarn bonds, and slippage in the specimen grips. At 60°C most of the coatings are highly amorphous.

The coated material, 5b, has an MD and TD Kevlar fabric base with a Dacron fabric bias ply. This combination of high- and low-modulus materials produces incompatibilities not evident in 5a. Considerable loss in strength was observed from room temperature to the cold environment for all test directions. In spite of this, the absolute strength is larger than for the control material, 5a. The higher strength obtained from the Kevlar is more demanding of the yarn-coating bonds. Apparently, bond toughness is less at low temperatures and widespread, random-bond failures occur, resulting in higher apparent strains and lower strengths in MD and TD tests. The coated material, 6b, is similar in construction to 5b except for relocation of the Kevlar MD and TD aligned fabric from the surface to near the centerplane. This produced a significant difference in the bias strength and elongation. Encapsulation of the Kevlar is improved by the provision of two shear surfaces instead of one. Apparently, this was sufficient to maintain functional yarn bonds to high load levels for the low-temperature bias tests. The nearly constant MD and TD strain-temperature relationship is further evidence of improved integrity. The loss in cold temperature MD and TD strength is similar to the 5b specimens. Since this test orientation is primarily a test of Kevlar strength, it is evident that fabric-coating bonds are too low to have a positive correlation strength with temperature.

Strain rates. - The Dacron composites show near independence to temperature in some tests, and a negative correlation in others. Strain rate was considered as a possible cause for the difference. The uniaxial tests of Reference 3 used an initial strain rate of 400 percent per minute, whereas the tests reported here used a rate of 67 percent per minute. In Reference 7, further strain-rate data are available on individual Kevlar-49 yarns tested under FTM 5102 at 0.17 percent per second and 800 percent per second. The high rate yielded break elongation values similar to the low rate, but tensile loads were about 15 percent less than obtained at the lower strain rate. Since strain rates of the current study were lower for Kevlar-49 based materials than those of Reference 7, the variability in test results of this report is probably not the result of the strain-rate variations.

Clamp effects. - The present study used different methods of clamping the specimen for each temperature condition. This does not present a problem when comparing different materials at a given temperature, but it does make it difficult to determine the effect of temperature on an individual material. The various clamping methods apparently had little effect on the baseline Dacron materials since there was good agreement with the data of Reference 3. Considering the material wrap of the D-ring grip, Figure 9, higher elongations can be expected for this method. Not only is it difficult to maintain a constant initial jaw separation between samples, but it is also difficult to establish the effective jaw separation. Specimen loads decrease exponentially around the curved pins with no sharp demarkation between the specimen, which is desirable when testing high strength material. It has the disadvantage that some finite load must be applied to the specimen before enough gripping force is developed to prevent slippage. The pre-loading

required depends on the coefficient of friction of the specimen and rings. The amount of slippage depends on the rate of loading. In Figure 22 the load elongation curves represent the results of an ambient test using the hydraulic jaws, and the results of a cold-temperature test using the sliding D-ring grip. Evidently, considerable initial elongation occurs for the D-ring.

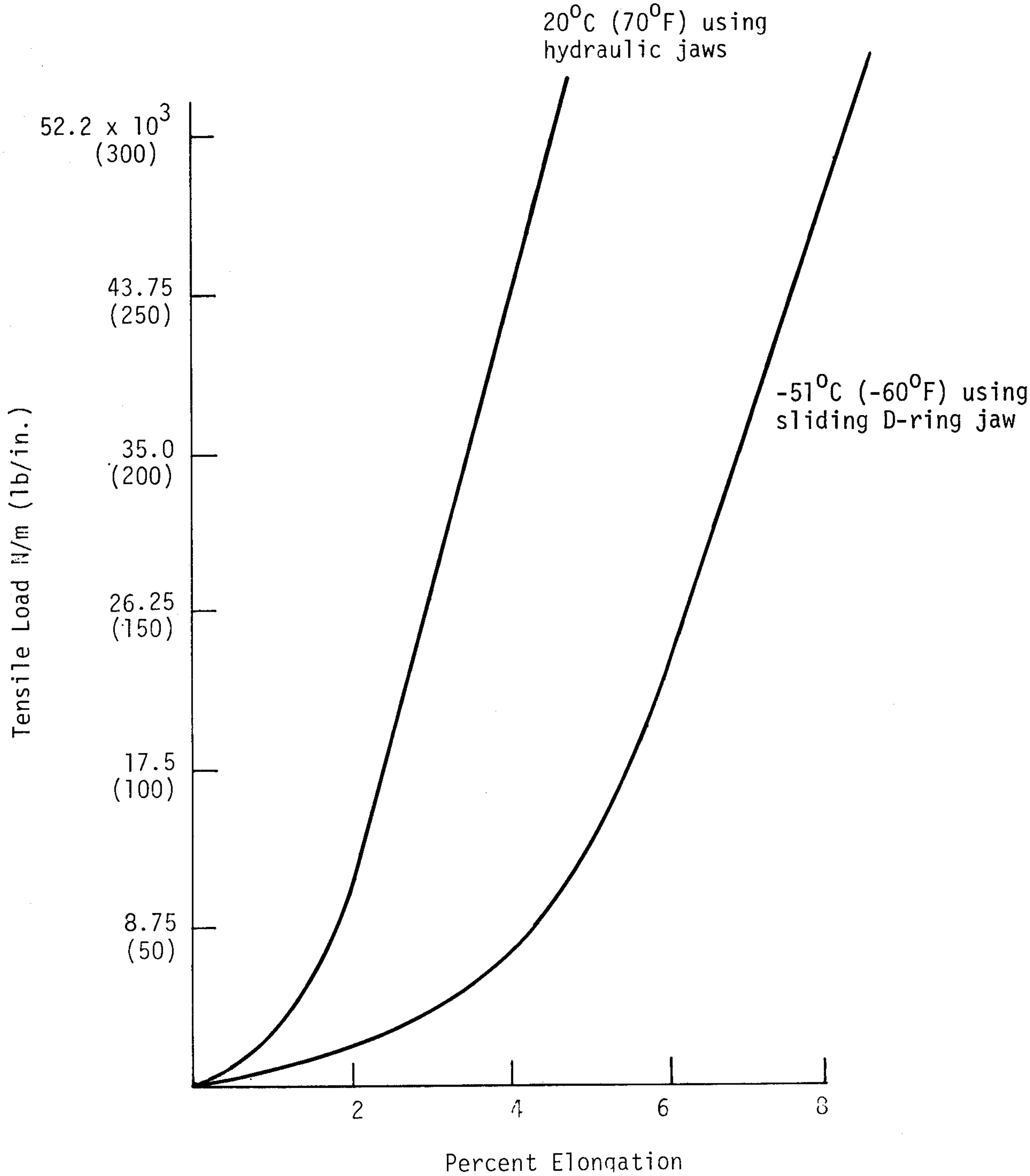


Figure 22. Comparison of MD Load and Strain in Material 2c at Two Temperatures and Two Grip Methods

After the load becomes sufficient to tension the material wrap and supply the necessary gripping force, the slopes of the two curves are similar.

Adequacy of bias ply. - The test data have consistently indicated lower bias strength compared to the MD and TD strengths. This has been attributed, primarily, to failure to obtain a full-strength contribution from all constituents in the bias tests.

It is also possible that the amount of bias reinforcement was insufficient to provide significant bias strength. The volume and stiffness ratios of bias-ply yarns to the MD and TD yarns are indicated below:

Material Code	Volume Ratio (Bias/MD and TD)	Stiffness Ratio (Bias/MD and TD)
2c	0.19	0.19
4c	0.19	0.19
5a	0.36	0.36
5b	0.42	0.04
6b	0.42	0.04
6c	0.13	0.13

The bias-yarn materials, 2c, 4c, and 6c, have a bias stiffness less than 20 percent of the MD and TD yarns which would indicate a low degree of isotropy. The control, 5a, has the highest stiffness ratio because of the high volume ratio and identical elastic moduli. Materials 5b and 6b show the lowest stiffness ratios, a result of the difference in elastic moduli of Dacron and Kevlar. Although 6b has a low stiffness ratio, it shows the best cold temperature isotropy. This suggests that the bias strength comes from the non-bias constituents because of efficient load transfer to MD and TD yarns when loaded on the bias. More consistent results and better isotropy could result from increasing the bias-stiffness ratio by substitution of Kevlar bias cloth for Dacron.

Strongest material. - Of all the materials tested, 6b showed the best strength and isotropy. This material is similar to 5b, having a Hypalon outer surface, polyurethane and Neoprene gas layers, a Dacron bias fabric, a Kevlar base fabric and an adhesive wash coat on the fabric. The Kevlar fabric is repositioned from the outer layer in 5b to near the centerplane in 6b. The improved diagonal performance of 6b is attributed to more uniform and symmetric loading when nearly equal amounts of other constituents are located on both sides of the Kevlar. This arrangement, however, may reduce the splice and seam strength obtainable, compared to composites with the structural fabric near one surface.

In comparing the tensile data of TABLE 4 and Figures 17 and 18, note that the higher performance of the 5- and 6-series materials compared with the 1-, 2-, 3-, and 4-series materials does not hold on a strength-to-weight basis. The 1- through 4-series materials are lightweight laminates ranging in weight from 1.9 N/m^2 to 2.7 N/m^2 (13 oz/yd^2 to 8.2 oz/yd^2). The 5- through 6-series

coated materials are heavier, as well as stronger, ranging in weight from 2.9 N/m^2 to 4.3 N/m^2 (8.7 oz/yd^2 to 13 oz/yd^2). The laminated control material weighed 2.5 N/m^2 (7.6 oz/yd^2), and the coated control material, 4 N/m^2 (12 oz/yd^2).

Further improvements in strength-to-weight performance of the 6b material, based on consideration of isotropic strength alone, may result from replacement of the Dacron bias fabric with a lighter Kevlar fabric or substitution of a triaxial Kevlar ply (References 8 and 9) for both fabrics currently used. Consideration of handle characteristics and crease degradation may indicate quite different modifications.

The strong influence of low temperature on adhesive strength and rigidity and the consistent evidence of bond failure indicate that better adhesives could significantly improve the Kevlar composite strength. This is further justification for the type of research described in Reference 6.

Peel Test Data

Peel test results are summarized in TABLE 6. Peel values were generally found adequate, based on conventional standards for inflatable structures, except for 6c where low peel values were obtained for the urethane to Kevlar and Kevlar bias yarn to Kevlar fabric bonds. The low peel strength between the Kevlar yarns and fabric is not surprising since these were bonded with a very light coat of adhesive. The low peel strength of the urethane to the fabric may indicate the presence of an incompatible fabric finish or residual lubricants from the weaving process. In anticipation of such conditions, all fabrics were wash coated with adhesive before further assembly. It is possible that the wash coating was insufficient on this particular sample, since the poor adhesion was localized. This was not representative of the other coated materials. Normal peel values for elastomeric coatings applied to fabrics range from 900 to 1200 N/m (5 to 7 lb/in.). Unfortunately, little peel test data were obtained for the coated materials because of a shortage of materials, precluding completion of the original test plan. Strength tests were judged more important to this study, and peel tests were conducted after other testing was completed with the remaining material. The inability to insert ply separators when fabrics were coated complicated the testing. Peel was initiated for the majority of the specimens by cutting with a razor blade. An attempt was made to separate the plys with solvents, but the solvents degraded the coating strength to the extent that the peeling could not be sustained without tearing the coatings.

TABLE 6. Peel Test Results

Material Code	Interface Tested*	Peel Strength N/m (lb/in.)		Coefficient of Variation
1a	Dacron x Mylar	770	(4.4)	0.124
	Mylar x Tedlar	424	(2.4)	0.103
	Mylar x Mylar	361	(2.1)	0.060
1b	Mylar x Kevlar	945	(5.4)	0.041
	Mylar x Mylar	452	(2.6)	0.141
2b	Tedlar x Mylar	396	(2.3)	0.074
	Kevlar x Mylar	858	(4.9)	0.046
2c	Tedlar x Mylar	434	(2.5)	0.060
	Mylar x FTL Bias	750	(4.3)	0.132
3b	Tedlar x Kevlar	784	(4.5)	0.111
	Kevlar x Mylar	1170	(6.7)	0.363
	Mylar x Mylar	518	(3.0)	0.444
4c	Tedlar x Saran	546	(3.1)	0.414
	Saran x Hytrel	308	(1.8)	0.187
	Hytrel x FTL Bias	1292	(7.4)	0.254
5a	Neoprene x Dacron	1050	(6.0)	0.48
5b	**			
6b	Neoprene x Dacron	1357	(7.8)	0.046
6c	Urethane x Kevlar	126	(0.7)	0.207
	Kevlar x FTL Bias	402	(2.3)	0.204

*All interface surfaces attempted are indicated in Figure 2.
**No peel data because of insufficient sample material.

Durability Test Results

Test data for crease effects, tear strength and puncture resistance relate to performance of the ten custom materials under handling, packing and wear in service.

Crease tests. - Data from crease testing are provided in TABLE 7 and Figures 23 and 24. Comparative coupon strength data are given for uncreased and creased specimens. Coefficients of variation are given to show the consistency of results. The Kevlar laminates, 1b, 2b, 2b, 3b, and 4a, exhibited high sensitivity to creasing, showing strength losses in the range of 33 to 59 percent. The Kevlar laminate with the least crease degradation was material 2b. The Kevlar laminates ranked in order of decreasing performance are 2b, 4b, 2c, 1b, and 3b. Materials 2c and 4c were nearly identical in crease degradation. These materials are very similar execpt that the higher modulus Mylar film in 2c is replaced by a bi-laminate of lower modulus Saran and Hytrel film in 4c. The results indicate that the reconfiguration had little beneficial effect on crease sensitivity. Both 2c and 4c have Kevlar bias yarns. If these two materials are treated as exceptions, then the crease performance may be said to vary inversely with laminate thickness. Materials 2b, 2c, and 4c were all designed to reduce membrane stiffness. Compared with the other Kevlar laminates, a small improvement was obtained, Figure 23.

TABLE 7. - Crease Test Results

Material Code	Control Break Strength N/M (lb/in.)	Control C.V.*	Creased Break Strength N/m (lb/in.)	Creased C.V.*	Percent
1a	4.24×10^4 (242)	0.053	3.94×10^4 (225)	0.070	7
1b	5.49 (314)	0.066	3.04 (173)	0.144	45
2b	5.55 (316)	0.121	3.72 (212)	0.075	33
2c	2.92 (323)	0.048	3.38 (193)	0.084	40
3b	5.87 (335)	0.029	2.42 (138)	0.130	59
4c	5.45 (311)	0.036	3.33 (190)	0.072	39
5a	3.72 (213)	0.022	3.54 (202)	0.025	5
5b	6.64 (379)	0.042	6.02 (344)	0.058	9
6b	6.52 (373)	0.053	6.37 (364)	0.118	2
6c	5.71×10^4 (326)	0.085	5.24×10^4 (299)	0.134	8

*Coefficient of variation.

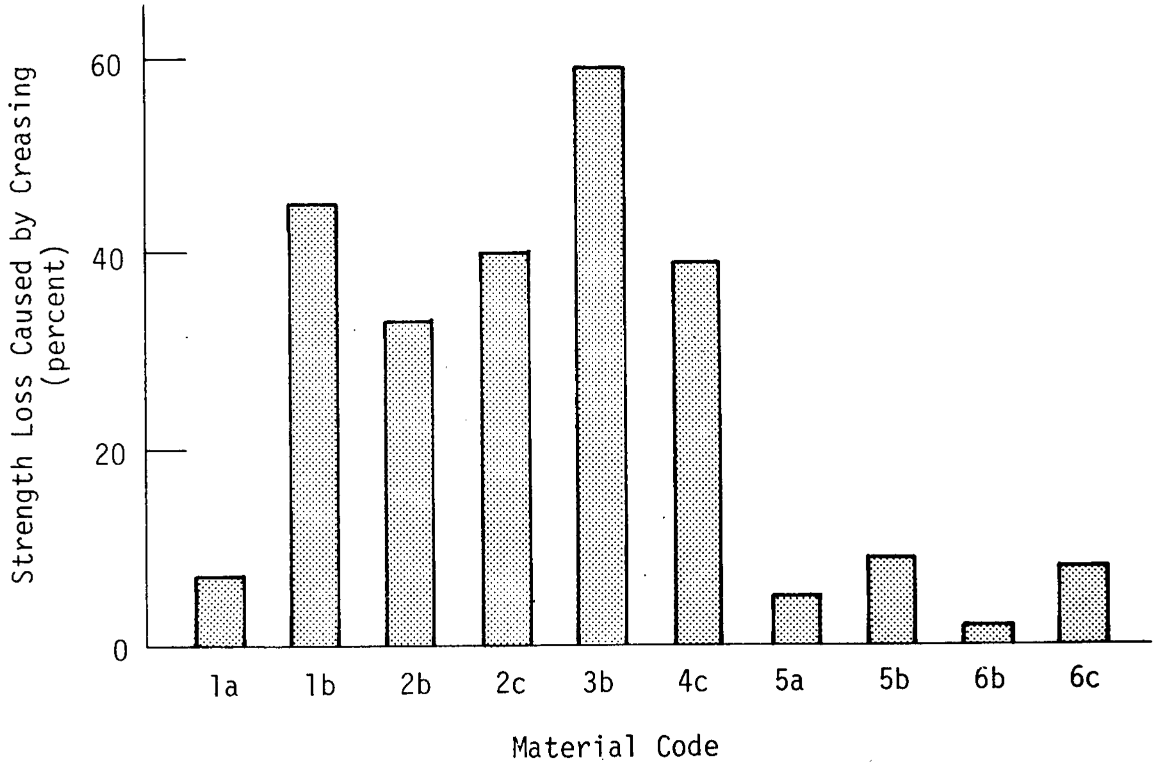


Figure 23. Comparison of Crease Performance

Materials 1b and 3b exhibited the worst crease performance. Apparently, high modulus film plys along with the Kevlar fabric, produce an undesirable laminar geometry. The failure to obtain the anticipated improvements from materials 2c to 4c is consistent with this conjecture. At the beginning of this study it was believed that both crease performance and handle characteristics could be improved by relocating the structural fabric nearer to the mid-plane of the laminate and by using more elastomeric gas membranes such as Hytrel® (4c). For the laminates, relocation of the Kevlar to the mid-plane was accomplished in 1b, 2b, and 3b. A slight improvement in handle did result from this change. However, crease performance reduced rather than improved. This might be attributed to an unproductive exchange in position of two plys having similar section moduli.

The coated materials (5a, 5b, 6b, and 6c) show marked improvements over the laminates in crease performance. This is clearly evident from the strength-loss column of TABLE 7 and Figure 23. The coated Kevlar material, 6b, even showed improvement over its Dacron-coated control, 5a. The 6b material is identical with 5b except for the repositioned Kevlar fabric. Relocation of the Kevlar was clearly a favorable change, reducing the 9-percent loss for 5b to a low of 2 percent for 6b. Material 6b has

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a low sensitivity to crease, although the factors responsible for this characteristic are not entirely clear.

Further investigation into the nature of crease degradation in Kevlar laminates and coated fabrications would be beneficial. Some related basic research has been reported in the development of FTM 5102. High twist levels in Kevlar yarns were found to degrade strength as much as 32 percent. Bending was found to be a secondary effect. Strength degradation under combined tension, bending, and transverse compression was greater than the sum of the individual degradations. The most significant of these factors is the transverse compression (load applied normal to filaments). For example, a strength loss of 25 percent was found for a compressive loading of 193 N/cm (100 lb/in.)

Since laminate yarns are more highly constrained because of the rigidity of the membrane materials to which the yarns are bonded, it is possible that high transverse compression occurs in creased laminates. Transverse compression for coated-Kevlar materials might be substantially less than for laminates since yarns are imbedded in a more elastic matrix. It is also reasonable to expect a reduction in transverse compression for laminates which contain more elastic membranes.

Strength-to-weight ratio is perhaps the most significant figure of merit for materials used in inflatable structures. This parameter is shown in Figure 24 for all of the materials, before and after creasing. In the absence of severe creasing, Kevlar laminates offer superior strength-to-weight performance compared to coated Kevlar materials. When hard creasing occurs, the severe degradation of the laminates and the mild degradation of the coated materials tend to equalize the strength-to-weight performance of the two types of materials. Figure 24 indicates that after crease degradation the Kevlar laminates (1b, 2b, 2c, 3b, and 4c) are comparable to the Dacron laminate control and to the creased, coated Kevlar materials. It is noteworthy that coated materials are competitive with laminates only if they are fabricated of Kevlar. For example, the coated Kevlar-49 materials exhibit about twice the strength-to-weight ratio of the coated Dacron material, even after crease degradation.

The characteristic lower strength-to-weight ratio of uncreased coated materials compared to the uncreased laminates is a direct result of the coating weight required to achieve gas permeability equivalent to the membrane constituent used in the laminates. For applications not requiring low permeability, coated Kevlar composites of higher strength to weight appear feasible. Research devoted to reducing permeability of coated materials per unit weight would be beneficial and rewarding.

Trapezoidal-tear tests. - Trapezoidal-tear results are summarized in TABLE 8 and are presented graphically in Figure 25.

The Dacron control materials exhibited the best tear resistance. Since tearing propagates by progressive fracture of individual yarns, open-weave fabrics of high denier yarn have a greater tear resistance

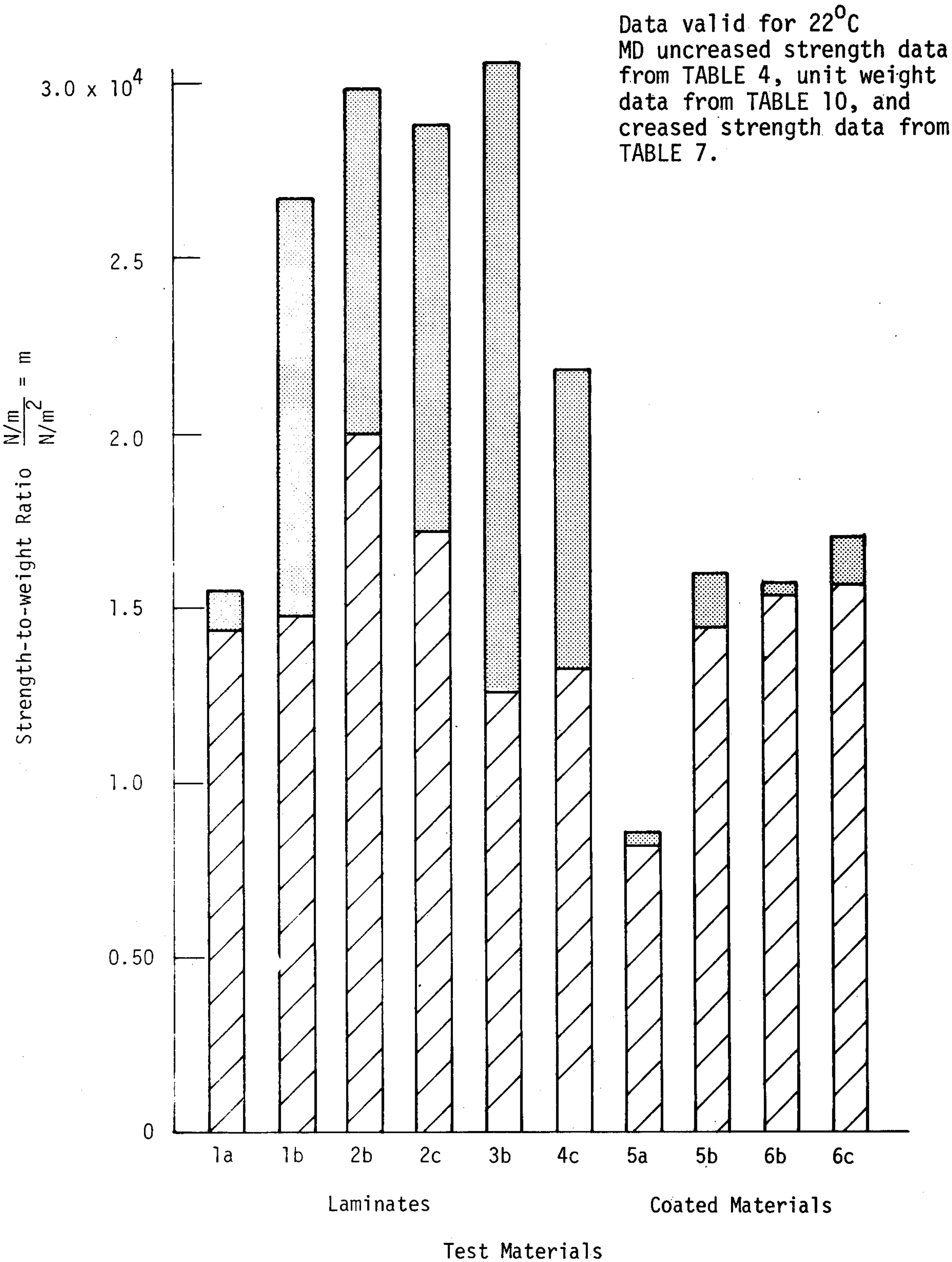

Figure 24. Structural Efficiency of Creased (shaded) and Uncreased Test Materials

than tightly woven fabrics of small denier yarns. The presence of bias yarns tends to raise the required tearing force. This can be seen in Figure 25 by comparing materials having a base fabric and a bias ply with materials having single fabric ("c" series materials have the Kevlar bias yarns).

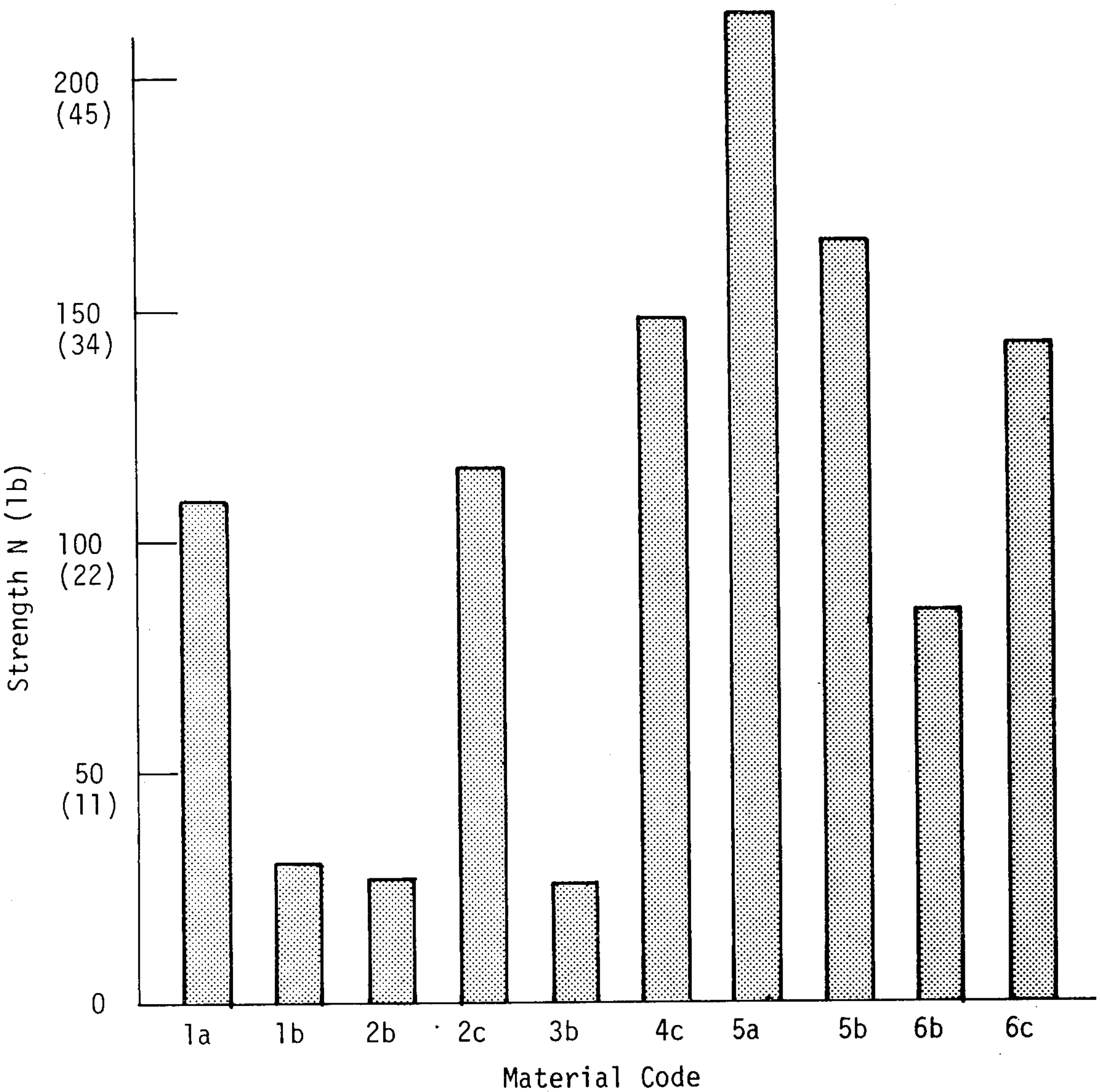

Figure 25. Tear Resistance of Test Materials

TABLE 8. Trapezoidal Tear Results

Material Code	Tear Force N (lb)	Coefficient of Variation
1a	109 (24.5)	0.200
1b	30 (6.7)	0.142
2b	27 (6.1)	0.147
2c	116 (26.2)	0.176
3b	26 (5.7)	0.023
4c	148 *33.4)	0.219
5a	224 (50.4)	0.236
5b	165 (37.1)	0.041
6b	85 (19.2)	0.068
6c	143 (32.1)	0.065

Puncture resistance tests. - The average force required to puncture machine-direction specimens of the test materials is given in TABLE 9.

TABLE 9. - Puncture Test Results

Material Code	Puncture Force N (lb)	Coefficient of Variation
1a	211 (47.4)	0.179
1b	143 (32.2)	0.314
2b	143 (32.2)	0.470
2c	133 (30.0)	0.125
3b	168 (37.8)	0.318
4c	125 (28.2)	0.149
5a	202 (45.4)	0.110
5b	209 (47.0)	0.034
6b	227 (51.0)	0.342
6c	278 (62.6)	0.218

To relate puncture resistance and material configuration, a linear, multiple regression analysis was performed for six variables:

Variable	Correlation Coefficient
Material thickness	0.707
Membrane or coating thickness	0.706
Membrane or coating strength	0.749
Yarn strength (fabric strength/yarn count)	0.343
Yarns per unit length (yarn count)	0.437
Fabric stiffness, E_t (force/unit length)	0.261

While puncture strength appears most highly related to membrane or coating strength, the true relationship is probably nonlinear and much more complex than assumed for this analysis. The relationship appeared to differ between coated and laminated materials, so the analysis was repeated, treating the two material types independently. Puncture resistance of laminated materials was then found to vary inveresely with fabric stiffness (correlation coefficient of -0.985). This indicates that puncture resistance may be significnatly influenced by the laminar configuration of a composite.

Handle Characterization Data

Results of handle measurements were supplied by NASA Langley Research center for the ten research materials, Reference 5, and are given in Figures 26 and 27. Improvement of the handle of Kevlar composites was a prime objective of this study.

Figure 26, reprinted from Reference 5, is included as background to indicate the value of the handle parameter, $H/\overline{H}$ of many conventional materials. All of the handle moduli H are ratioed to the reference modulus $\overline{H}$ = 2.17 N/cm^2 (3.15 lb/in.^{2}) of the widely available and well defined nylon parachute cloth, MIL-C-7020F, Type 1 (Reference 10). Note the three order-of-magnitude range in $H/\overline{H}$ denoting how readily a material can be creased, folded, packaged and draped over compound curves. Only four of the research materials (1a, 1b, 5b, and 6b) are shown in Figure 26. Material 5b appears once for the hand-fabricated material of this contract, and once for the production-scale material developed under contract NASL-11694. The 1b material shown in Figure 26 ($H/\overline{H}$ = 102) was also manufactured on full-scale processing equipment. Its hand-produced equivalent has a $H/\overline{H}$ = 106. Materials with $H/\overline{H} \geq 40$ may be considered difficult to fold, crease, and flex, without specially engineered processes and controls. Materials to be folded, packed, and deployed should have lower handle ratios. Development of a Kevlar laminate of strength similar to 1b through 4c with an $H/\overline{H}$ value below 40 would be a highly desirable objective for further research.

In Figure 27 the $H/\overline{H}$ ratios are shown on a linear scale for comparison. The laminate series 1a through 4c all have inherently high handle moduli.

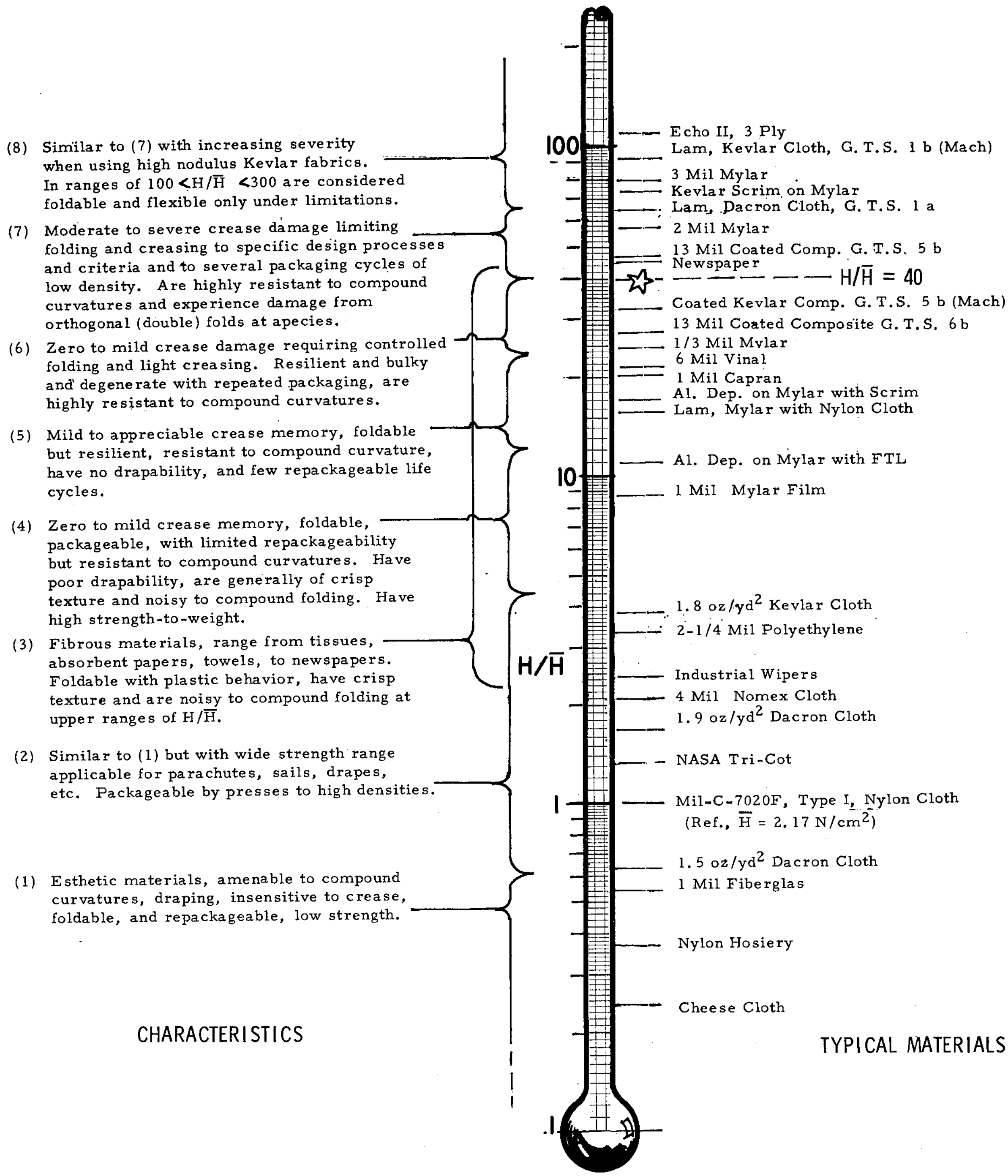

Figure 26. Handle Comparisons

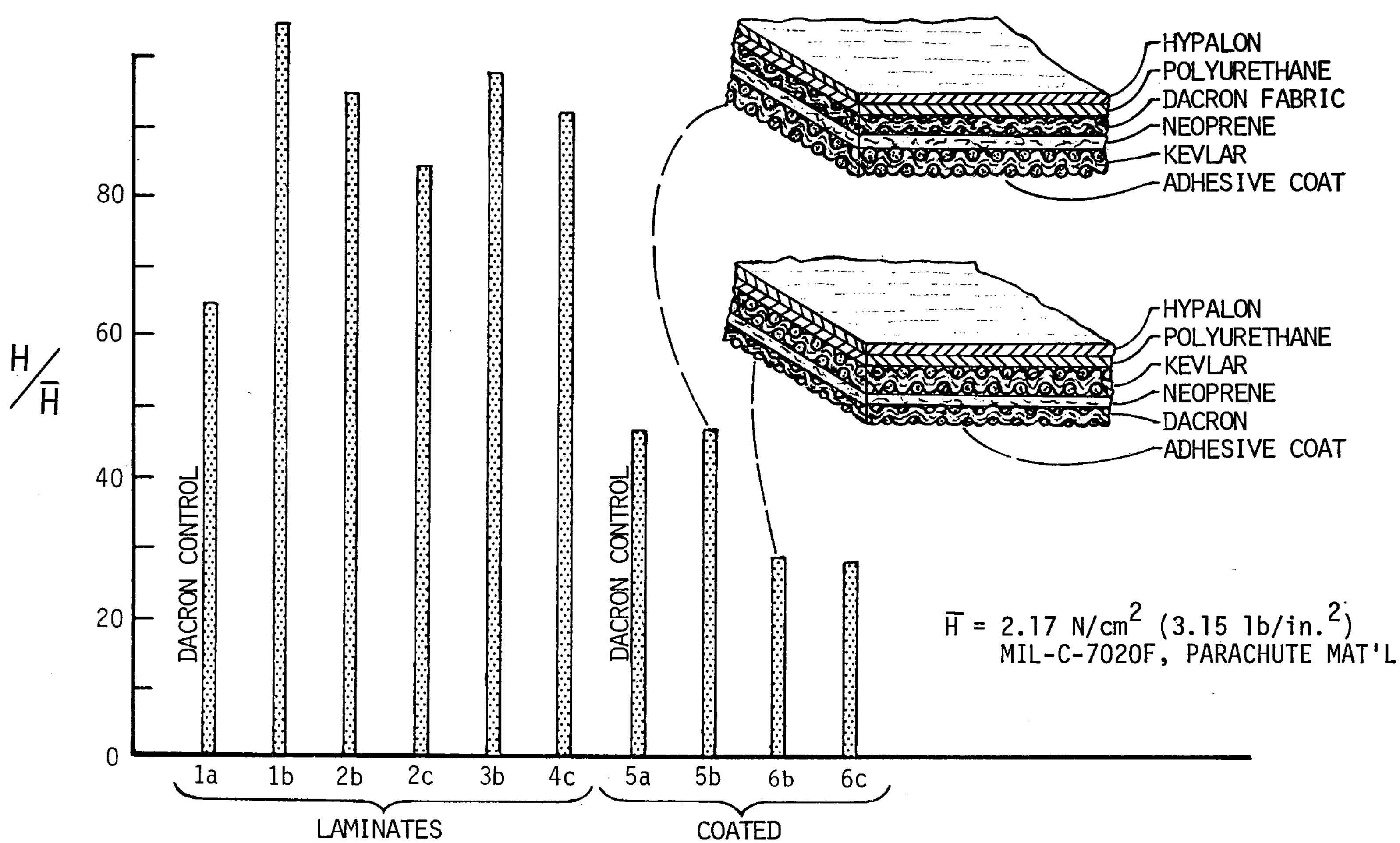

Figure 27. Comparison of Handle Moduli of Test Materials

Compared with the Dacron control laminate, the Kevlar laminates have inferior handle properties. Laminate 3b is a reconfiguration of 1b, placing the Kevlar fabric near the centerplane. This achieved only an 8-percent reduction in handle modulus which is attributed to the unproductive exchange in position of plys having similar section moduli. The Mylar film is an effective gas barrier, but significantly increases the handle modulus of all materials in which it is used.

The coated materials (5a through 6c) have considerably better handle than the laminates and the same or better handle than the coated Dacron control. The exchange in position of the Dacron and Kevlar fabrics from 5b to 6b of the figure reduced the handle modulus by 40 percent, as well as reduced crease strength loss from 9 to 2 percent. Although only trivial differences were observed in the MD tensile strength, 8- to 19-percent increases in tensile strength were observed in the transverse direction, 15- to 32-percent increases in the elevated temperature bias strength, and 63- to 96-percent increases in low temperature bias tensile strength were obtained for 6b, compared to 5b. The reconfiguration was designed to improve handle modulus, but it resulted in significant all-around benefits.

Material 6c exhibits a handle modulus similar to 6b. However, 6c has Kevlar bias yarns and inferior bias strength, somewhat lower MD and TD tensile strength, and about four times the strength loss from creasing as 6b. The favorable performance of 6b suggests that mid-plane location of high strength, high modulus constituents yields the most efficient composite.

None of the Kevlar laminates possessed a handle as low as the Dacron laminate, although both coated Kevlar materials (6b and 6c) showed appreciable improvement over their Dacron counterpart. Materials 6b and 6c were comparable in handle, and the lowest of the ten materials tested. All of the coated materials showed marked improvement in handle characteristics over the laminates.

The concept of handle modulus used here should be generally useful for establishing rational design criteria for flexible composite materials requiring folding and handling.

Material Weight Data

Material weights and thickness for the material configurations of Figure 2 are presented in TABLE 10.

TABLE 10. - Weight and Thickness of Test Materials

Material Code	Weight per Reference Area*		Thickness**		
	N/m^2	(oz/yd^2)	μm	(mils)	Variation
1a	2.73	(8.20)	272	(10.7)	0.030
1b	2.06	(6.20)	196	(7.7)	0.051
2b	1.86	(5.59)	194	(7.6)	0.027
2c	1.96	(5.91)	229	(9.0)	0.032
3b	1.92	(5.77)	202	(8.0)	0.053
4c	2.50	(7.52)	289	(11.4)	0.057
5a	4.32	(13.00)	372	(14.6)	0.016
5b	4.14	(12.45)	355	(14.0)	0.023
6b	4.14	(12.45)	321	(12.6)	0.010
6c	3.33	(10.02)	351	(13.8)	0.017

* Weight was computed as the sum of the constituents weights.
**Thickness was determined by micrometer measurement.

Other Characteristics

The ten materials of this investigation were not analyzed for creep and relaxation effects or thermal and electrical characteristics such as absorptivity, emissivity, reflectivity, transmissivity, heat capacity, conductivity, dielectric strength, outgassing, and vapor conductivity.

CONCLUDING REMARKS

Six laminated and four coated composite materials were designed, fabricated and tested to investigate the effects of high modulus, high strength Kevlar fabric and yarn reinforcements when used in place of Dacron. Emphasis was placed on acquiring superior strength to weight along with acceptable peel strength, tear resistance, puncture resistance with good crease performance and improved handle characteristics.

Materials were configured to determine the effects of relocating the most rigid constituents near the mid-plane, of replacing high modulus film layers with more elastic film, and of using open scrims of Kevlar yarn in place of bias fabtics.

The fabrication techniques used in specimen preparation were consistent with conventional production-scale laminating and coating processes.

Because this was a preliminary investigation of many configurations and was limited to small handmade specimens, strength measurements were made by uniaxial tensile tests. These provide relative or comparative data, but

they fail to properly involve all of the structural constituents as in bi-axial tensile testing. Standard coupon tensile tests were found inadequate for materials containing diagonal fiber constituents because of the high-length-to-width ratio and free edges. This effectively reduces the specimen's test length causing increased local strains above the average indicated strain, poor transverse load distribution, local stresses higher than the average stress, and limited strength contributions from diagonal reinforcements.

Most of the data indicated poor strength and stiffness isotropy at room temperature, although some improvement was noted at cold temperatures. The materials with no bias reinforcement were particularly anisotropic. The materials having Kevlar scrim bias reinforcements appeared weaker in the bias direction than similar materials without bias reinforcement which is attributed to the similarity in bias yarn spacing and test specimen width. The laminate employing Hytrel film in place of Mylar exhibited a comparative strength loss and increased anisotropy as a result of the substitution. Because of the inadequacy of the coupon test to properly load materials with diagonal constituents, the anisotropy observed may not be representative.

The effect of temperature on stress and strain was found to vary widely but consistently with type of specimen, material, and fabrication details. Two distinctly different structural mechanisms were involved for bias-direction testing and for MD or TD direction testing. A strong temperature effect was produced by two thermomechanical phase transitions in the adhesive within the range of test temperatures. The bias direction, strength, and elongation change after a temperature drop from 22°C to -51°C is opposite to the change for the MD and TD direction tests. In the bias-direction tests elongation is reduced with temperature which is attributed to the order of magnitude increase in stiffness of the adhesive along with moderate stiffness increases of the other constituents. The adhesive phase changes at low temperature produce a more rigid fiber matrix and enhance the stiffness contribution of diagonal elements not otherwise involved because of the narrow specimen width and free edges of coupon specimens.

The bias-direction strength was either unchanged or increased by the temperature reduction. Bias strength depends on the strength contribution from diagonal elements and the degree of matrix embrittlement which increases sensitivity to failure from local stress concentrations. Compatibility of bond shear strength with yarn tensile strength, use of Kevlar in place of Dacron, the presence or absence of bias reinforcements, and the spacing of bias reinforcement fibers also have significant effects on bias strength.

For MD and TD direction tensile tests, the change in failure strain with temperature reduction is attributed to progressive bond failures. For these tests, diagonal fibers were Dacron and not Kevlar, so adhesive stiffening at low temperatures had a smaller effect on strength. MD or TD direction yarns were loaded directly by the grips without significant load transfer through the adhesive. MD and TD break elongations were in excess of the characteristic Kevlar failure strain, suggesting that progressive bond failure occurs. There was evidence that the adhesive bond to Kevlar yarns is considerably less than available fiber tensile strength.

The Dacron laminate exhibited a greater increase in MD and TD direction strength and strain with temperature drop than the Kevlar laminates. This is attributed to the better match of bond shear strength and Dacron tensile strength. For materials with both bias fabric and MD and TD fabric reinforcement, the differences at -51°C between bias and MD or TD direction test data are less since all specimens have diagonal elements for all test directions. The test direction showing greatest sensitivity to temperature was the one where the heaviest Kevlar fabric ply was diagonally oriented to the load. This effect was not apparent for materials having Kevlar bias yarn reinforcement which may be attributed to the test method deficiency noted above or to an insufficient amount of bias reinforcement.

The effect of material configuration on tear resistance was the same for Kevlar and Dacron materials. Open weaves of high densier yarns have greater tear resistance than tightly woven fabrics with small denier yarns. This feature permits the designer to alter tear strength without affecting tensile strength.

Puncture resistance of the materials under tension was found to be inversely related to fabric stiffness for the laminates and inversely related to coating thickness for the coated materials.

Creasing of Kevlar laminates reduced the strength-to-weight ratio considerably. Strength loss after creasing was comparatively small for the coated Kevlar materials. The strength-to-weight ratio of laminated and coated Kevlar materials were similar after creasing.

After creasing, the strength-to-weight ratios of Kevlar laminates were generally less than that of Dacron laminates, but coated Kevlar materials retained about twice the strength to weight of coated Dacron samples.

The material showing the least strength loss from creasing was the coated Kevlar material (6b) with the Kevlar fabric located near the mid-plane.

Material handle measurements were provied by NASA Langley Research Center using a method proposed by the government monitors. A handle modulus was defined that is potentially useful for ranking laminar materials for applications where material drape, repeated high density packing, and strength degradation from creasing, are important.

Results reported in this paper, based on coupon tensile tests and limited laboratory-scale material specimens may be misleading. More conclusive measurements would require material specimens made on production-scale equipment, and biaxially tested in a cylinder configuration. Investigations conducted under this contract have considerable value, however, as a precursor to more sophisticated research and were one to two orders of magnitude less in scope and cost than a comprehensive and thorough investigation.

The following effects observed during this effort should be considered in any future development:

1. Locating constituents with high strength and modulus near the mid-plane increases composite strength, improves strength retained after creasing and is significant in reducing the handle modulus.

2. High tensile modulus films increase crease sensitivity and degrade handle and should be avoided whenever gas permeability considerations are secondary.

3. Use of more elastic films in place of high modulus films lowers crease sensitivity and improves handle.

4. Tear strength is increased for open weaves and large denier yarns and decreased for tight weaves and small denier yarns of the same tensile strength.

5. A fabric bias reinforcement or a triaxial fabric appear to be superior to an open scrim bias reinforcement.

6. Puncture resistance in laminates is inversely related to fabric stiffness and inversely related to coating thickness for coated materials.

7. Coated Kevlar materials with increased strength-to-weight performances are feasible in applications where gas permeability is not an important consideration.

8. Kevlar laminates provide superior strength-to-weight characteristics in applications where creasing and packaging can be minimized.

9. In applications where lightweight and good handle are important, Hypalon coating is to be preferred to Tedlar film as a UV barrier because of its lower stiffness and lower density.

10. The coated material (6b) with Kevlar fabric at mid-plane displayed the best distribution of reinforcement elements and strength isotropy, low crease degradation, the lowest handle modulus, good strength-to-weight properties and acceptable tear and puncture performance. Additional development of this material would be of considerable value in promoting the objectives of this investigation.

11. The strength and elastic properties of laminates and coated composites are subject to near discontinuous changes with temperature where constituents undergo thermomechanical phase changes within the service temperature range. Test data points should be adequately spaced to define such changes.

12. More rigid adhesives and film constituents improve the integration of fiber components in composites and generally reduce strain. However, the associated reduction in ductility of the matrix constituents increases sensitivity to local stress concentrations and reduces average composite strength.

13. The performance of composites is strongly influenced by the strength and ductility of the adhesive. Shear strength of the adhesive used (Sheldahl A-102 resin) was well matched to Dacron tensile properties but bond strength to Kevlar was considerably less than the filament strength. Further adhesive research is essential to increase fiber bond strength and to reduce the phase transition temperature below the service temperature range, if the potential advantages of Kevlar yarns are to be fully realized.

14. For a maximum return on research expenditures, a more sophisticated test program should yield the usual research data, carefully analyzed failure modes and failure sequences, photographic records of progressive deformations and terminal failures, transverse strain characteristics, measurement of out-of-plane deformation and of diagonal or axial tension fields, checks on grip slippage and grip uniformity, observation of local filament bond failures, evidence of relaxation, and thorough records of photogrametric details such as camera coordinates and lens properties. Data on individual constituents such as stress-strain information, tensile, peel and shear strengths, creep and relaxation rates, and thermomechanical spectra should also be acquired.

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